PAUL BAKER
NTSB

UNITED STATES of AMERICA

FEDERAL AVIATION ADMINISTRATION

AIRCRAFT CERTIFICATION SERVICE

ENGINE AND PROPELLER DIRECTORATE

TITANIUM ROTATING COMPONENTS REVIEW TEAM REPORT

December 14, 1990

UNITED STATES of AMERICA

FEDERAL AVIATION ADMINISTRATION

AIRCRAFT CERTIFICATION SERVICE

ENGINE AND PROPELLER DIRECTORATE

TITANIUM ROTATING COMPONENTS REVIEW TEAM REPORT

[redacted]

Joseph G. Costa

[redacted]

Raymond E. Gonzalez

[redacted]

Robert E. Guyotte

[redacted]

Daniel P. Salvano

[redacted]

Thomas Swift

[redacted]

Robert J. Koenig, Chairman

December 14, 1990

TABLE OF CONTENTS

VOLUME 1, PUBLIC REPORT

VOLUME 2, PROPRIETARY INFORMATION (Not Releasable)

SECTION:

1. TITANIUM INDUSTRY DATA COLLECTED
(Filed alphabetically by company name)

2. TITANIUM REVIEW *TEAM'S* ANALYSES OF DATA

SECTION 1, **EXECUTIVE SUMMARY**

In accordance with its Charter (Section 4.A of this report), the Titanium Rotating Components Review Team (TRCRT) visited the 23 organizations and facilities listed in Section 9.A, in order to collect the data necessary for a comprehensive review and analysis. Specifically, the visits were for gathering information to assess industry practices, and were not audits of any individual facility or organization. The Review Team considered all pertinent design, manufacturing, quality control, and inspection procedures used in the production of life-limited, rotating, high energy, titanium components; and has developed recommendations for their safety improvement.

It was agreed with the management of the Engine and Propeller Directorate that the Titanium Review Team could best spend its efforts, considering a reasonable time frame and the large size of the engine manufacturing and user industry, by limiting the scope of the review to the design and manufacturing (including non-destructive inspection (NDI)) phases of the life cycle of titanium critical parts. That is, from concept and mine-ore to completion of airworthy finished parts, not from cradle to grave. A detailed review of the continued operational safety procedures (specifically operator NDI's), from the time that life-limited parts enter service with the user until their permanent retirement, was not conducted by this Team.

Consequently, 1 foreign and 5 domestic engine manufacturers were visited, covering all aircraft turbine engine types (i.e. turbofan, turboprop,' and turboshaft). In addition, telephone discussions were held with 3 other engine manufacturers: one domestic and two foreign. Individual FAA visits to the sub-tiers of titanium suppliers of these 9 engine companies were included, going all the way down the chain to the producers of elemental titanium (i.e. "sponge"). To encourage uninhibited discussion, no representatives of the supplier companies' customers were in attendance at the supplier visits.

Virtually all of the companies contacted were very cooperative with facility tours, information sharing, and assistance from their top level personnel, downward: and proprietary information never before disclosed to the FAA, but important to the Review Team's purpose, was received. Since, in several cases, the suppliers selected for visits provide premium quality titanium products to still other engine manufacturers (in addition to the nine previously referenced), it is believed that a very representative cross-section of industry practices was obtained.

Therefore, this report is meant to be a critique of the industry as a whole, and should not be taken as criticism of any individual company. Although it was found that some engine manufacturers and some individual suppliers are technologically or qualitatively more advanced or more thorough (than their peers) in the management of safety critical titanium products, no serious safety deficiencies unique to any one company were discovered.

Certain statements in this report will apply only to 1 or 2 "non-typical" companies, in order to highlight uncommon but important beneficial or detrimental practices. On the other hand, because this review encompassed only a sample (albeit a large sample) of companies, as opposed to the entire population of companies in the industry, certain general otatements should only be construed as "typical". Hopefully, these concepts will be clear in the context of each individual subject.

In order not to divulge company proprietary information, and still be able to produce a report available to the public, it was decided to segregate the report into two volumes: therefore, Volume 1 is the public portion, and Volume 2 contains all of the proprietary data collected, as well as the analyses of this data as performed by the Team.

Based on the Sioux City accident, it is clear that improvements are necessary in total aircraft system survivability. This can be accomplished in two ways: (I) by improving the ability of the aircraft to withstand a massive sub-system failure without catastrophic results to the total system (redundancy, hardening or shielding, spacing of critical sub-systems, etc.), and (2) by improving the reliability/durability of individual sub-systems to avoid massive failure in the first place.

The total aircraft system approach is now described in Advisory Circular No. 20-128, "(Airplane) Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor and Fan Blade Failures", dated March 9, 1988. But the DC-10-10 airplane vas designed in the mid 1960's, before these guidelines were formalized, and therefore, it is not surprising that the DC-10 did not equal all of today's design standards in this regard. Subsequent to the Sioux City accident, the Transport Aircraft Safety Subcommittee *(TASS)* was chartered by the Administrator of the FAA to study and make recommendations in both of the above areas (i.e. total system approach; and sub-system reliability, including engines).

Since a contributing cause of the Sioux City accident was quickly determined to be the fatigue failure of a rotating, high energy, titanium component (the fan disk) within one of the CF6-6D engines, the TRCRT was chartered to review the design, manufacturing, inspection, and life management procedures of such parts (as used in all types of commercial aircraft turbine engines), and to make recommendations for improvement of their structural integrity, where possible.

We found today's design, manufacturing, and quality control system for safety-critical titanium rotating parts to be much better than that of the early 1970's when the Sioux City accident-disk was made. There has always been, and still is, more-or-less-continuous improvement in the system, but 1984 was a sort of watershed year when a significant number of important improvements were incorporated. Two or three engine manufacturers are primarily responsible for this enduring effort.

It appears possible that titanium vacuum arc remelt (VAR) technology may be approaching state-of-the-art minimum limitations in defect size and defect rate: but there is, definitely, still room for improvement in sponge production, housekeeping and material cleanliness procedures up through the final melt, NDI techniques, and structural design technology.

No machine or system is perfectly without risk to humans: and engineers understand that, realistically, rare random failures of mechanical systems will probably always occur even though their rate can be continually reduced. Fortunately, some new technologies are now available which promise a substantial reduction in disk failures from metallurgical defects. These are: vacuum distillation finishing for sponge, and cold hearth melting for ingots, both of which are advances in the production of clean raw material; and Fracture Mechanics analysis, and Weibull and Joint-Probability reliability analyses, which can make the design subgtantially more tolerant of defects.

The Review Team concludes that cost-effective safety improvements are possible in the subject components, and outlines recommended methods by which this may be accomplished. The Findings, Conclusions, and Recommendations in Sections 6, 7, and 8, respectively, of this report are submitted in fulfillment of the TRCRT's Charter, and as a contribution to the overall aircraft safety improvement effort.

SECTION 2

DEFINITIONS (as used herein)

Beta Flecks:	a defect consisting of beta stabilizer element eegregation.
Defect:	a harmful, or potentially harmful, imperfection.
DVM:	double vacuum melting, also known as: DM for double melt, and double VAR for double vacuum arc remelt.
ECI:	eddy current inspection.
Etch:	acid and/or electrolytic surface treatment used to visually highlight variations in the grain structure of a material, to facilitate visual examination and evaluation. Ammonium bifluoride etch, and blue etch anodize are the most common etches for titanium.
FBH:	flat-bottomed hole. Because of good ultrasound reflection, these are machined into metal blocks for calibration of ultrasonic test equipment.
FPI:	fluorescent penetrant inspection.
High Density Inclusion (HDI):	defects consisting of inclusions of high density elements such as tungsten or molybdenum. These elements also have a substantially higher melting point than titanium, and do not easily dissolve in the molten metal. HDI's are readily detectable by X-ray, and are detectable by UT.
High Interstitial Defect (HID):	same as Type I defect.
Inclusion:	localized, undissolved foreign material, or specification material, segregated from the matrix.

Indication: a discrete and reproducible response, caused by a physical anomaly in or on the part or material being evaluated, when specific testing input is introduced by one or more of various NDI techniques. The physical anomaly disclosed by the indication is then determined, through further and/or more detailed examination, to be either a harmful or benign imperfection or feature.

Low Density Inclusion (LDI): any inclusion of normal or lower density as compared to the matrix. (Type I defects are LDI's).

NDI: non-destructive inspection. Also known as non-destructive testing (NDT), and non-destructive evaluation (NDE).

POD: probability of detection. The POD, for all defects of a given size and type, is the fraction (of the total number) that will be detected by an NDI system when applied by representative inspectors to a specific population of structural elements in a defined environment.

Premium Quality Titanium: engine disk quality titanium. Also known as premium grade, and rotor grade, titanium.

Rutile: the typically reddish-brown, but sometimes lustrous red or black, natural mineral form of titanium dioxide, TiO_2, usually also containing a little iron and sometimes occurring as beach sand. It is used in making paints and fillers, as the source of titanium metal, and as gemstones.

Segregation: non-uniform distribution of impurities, inclusions, crystal phases, grain sizes, and/or alloying constituents in metals. (cont'd)

Segregation (cont'd): Arises from the process of solidification, and may persist throughout subsequent heating and working operations.

Tickle: jargon for $TiCl_4$ (i.e. titanium tetrachloride). $TiCl_4$ is chemically reduced, usually by reacting with magnesium or sodium, to form pure titanium (sponge) plus byproducts.

TVM: triple vacuum melting, also known as: TM for triple melt, and triple VAR for triple vacuum arc remelt.

Type I Defect: interstitially stabilized, hard, brittle, alpha-phase region (inclusion) in a titanium alloy. These defects are often accompanied by voids and cracks which make possible the detection of Type I defects by ultrasonic testing.

Type II Defect: aluminum-rich alpha stabilized segregation region in a titanium alloy, with a hardness only slightly higher than the adjacent matrix.

UT: ultrasonic testing: same as ultrasonic inspection.

VAR Furnace: vacuum arc remelt furnace. A consumable electrode, electric-arc heated, melting furnace operated under internal vacuum with the metal to be refined forming the consumable electrode. This type of melting furnace is universally used for refining and homogenizing premium quality titanium alloys.

Void(s), Clean: an unfilled space(s) appearing in the grain structure as a result of strain induced openings, or entrapped gas bubbles, without evidence of Type I or Type 11 defects.

Winning: extracting or producing, through chemical and/or physical processing, pure metal from ore.

SECTION 3

BACKGROUND MATERIAL

UNITED AIRLINES, INC.
McDONNELL-DOUGLAS DC-10-10 ACCIDENT
SIOUX GATEWAY AIRPORT, SIOUX CITY, IOWA

On July 19, 1989, United Airlines Flight 232 was on a regularly scheduled transit from Denver, Colorado to Chicago, Illinois, with 285 passengers and 11 crew members on board. While in level flight at 37,000 feet and Mach 0.83 there was a loud report, followed by vibration and/or shuddering of the aircraft, sensed by the flight crew. The center engine (position number 2) had incurred an inflight separation of the stage 1 fan disk with subsequent damage to the aircraft, resulting in the depletion of hydraulic fluid from all three systems powering the flight controls.

The aircraft flew for 44 minutes after the disk separation, with the crew experiencing difficulty in controlling the aircraft due to the loss of hydraulic power to the flight controls. Flight 232 crashed during landing at Sioux Gateway Airport, Sioux City, Iowa. Fatalities included 110 passengers and one flight attendant.

The United Airlines fnc. airplane, a McDonnell-Douglas DC-10-10, carried United States registration number N1819U, and had accumulated 43,401 hours and 16,997 cycles, since new. The aircraft was powered by three General Electric CF6-6D high bypass-ratio turbofan engines, each rated at 39,300 pounds of takeoff thrust (at static, sea level, standard day conditions). The aircraft's engine historical data are as follows:

Engine Data	Number 1	Number 2	Number 3
Serial number	451-170	451-243	451-393
Total time (hours)	44,078	42,436	39,338
Total cycles	16,523	16,899	11,757
Time since last maintenance (hours)	1,047	2,167	338
Cycles since last maintenance	358	759	116
Time since last shop visit (hours)	3,635	2,170	338
Installation date	9 May 88	25 Oct 88	11 June 89

The stage 1 fan disk, Part Number 9137M52P36, Serial Number MPO 00385, made of Ti 6-4 material, was installed in engine 451-243 in July 1988, during an engine shop visit. The engine at the time of installation had accumulated a total of 40,266 hours and 16,139 cycles, since new: and at the time of the accident had accumulated a total of 42,436 hours and 16,899 cycles. The stage 1 fan disk had accumulated a total of 41,009 hours and 15,503 cycles since new, at the time of the accident. The last shop visit of engine 451-243 was 760 flight cycles prior to the accident, and occurred from February to September 1988. Engine removal was for causes other than the stage 1 fan disk, however, a fluorescent penetrant inspection of the disk was accomplished at that time, together with a disk dovetail slot ultrasonic inspection and recoating. No crack indications were reported during those inspections.

FAN DISK INVESTIGATIONS

The factual information contained in this background summary consists of that material which was presented at the Sioux City public hearing on October 21, 1989. Additional examination has been performed on the Sioux City accident stage 1 fan disk, serial number MPO 00385, large and small segments to further characterize the material defect.

On October 10, 1989 approximately two-thirds of the stage 1 fan disk, part number 9137M52P36, serial number MPO 00385, from the number 2 position was found in a corn field in Alta, Iowa. The disk condition was characterized as having a wedge shaped piece missing which encompassed 11 blade slots at the rim outer diameter and a 4 inch segment at the bore inner diameter. The smaller segment of fan disk was found on October 13, 1989. The two disk segments were returned to the General Electric facilities in Evendale, Ohio.

The smaller segment was secured in a safe area in the as-received condition. The larger segment was subjected to metallurgical examination. Visual examination of the disk revealed two main fractures, one on a radial plane extending between the bore and the number 10 dovetail slot and one on a skewed plane intersecting the bore and extending to the number 2 dovetail slot. Upon further examination of the near-radial-plane fracture surface, evidence of a pre-existing fatigue crack was observed on the bore inside diameter. The fatigue crack was approximately 1.3 inches in surface length, running axially along the bore surface, and about 6.5 inches deep.

Microscopic examination of the bore diameter surface revealed a cavity which measured approximately 0.055 inches axially and 0.012 inches deep. The origin for the fatigue crack emanated from the bottom of this cavity. A fatigue striation density audit of the fracture surface found the failure mode of the fan disk to be in low cycle fatigue. A striation count of 14,000 to 16,000 cycles was observed.

Metallography, Hardness

A step-polishing procedure was used to examine the microstructure surrounding the cavity. As the polishing steps approached the center of the cavity the microstructure transitioned from areas of enriched alpha to larger areas of pure primary alpha phase (stabilized alpha). Further examination also revealed the presence of micro-porosity associated with areas of enriched alpha and subsurface micro-cracks. The micro-cracks were located within areas of stabilized alpha. In the stabilized alpha areas, hardness ranged from 39 Rockwell C to 51 Rockwell C. Microprobe results indicated that the concentration of aluminum and vanadium decreased and that the concentration of nitrogen increased, as the specimen was polished near the cavity.

THE SISTER DISKS

In the sister-disk inspection program, those disks which were determined to have been manufactured from the same heat of material (Timet heat K8283) as the disk involved in the Sioux City accident, were removed from service for full metallurgical evaluation. According to Timet records, heat # K8283 was double vacuum melted at the Timet facility in Henderson, Nevada, and subsequently converted from ingot to billet at Timet's Toronto, Ohio plant. Forging of the disks was performed by Alcoa. Billet map rgcords indicate that a total of 8 stage-1 fan disk forgings (serial nos. AJV 00381 through AJV 00388) were manufactured from this ingot, during the 1971 time frame. Seven of the forgings produced were found to be acceptable per General Electric Aircraft Engines' immersion ultrasonic inspection procedure. One forging was found to have a rejectable ultrasonic indication. In reviewing available manufacturing records it could not be conclusively determined whether this forging was S/N 381 or 385. For purposes of this discussion, it is assumed to be S/N 381 unless proven otherwise.

In this sister-disk inspection program, the parts were returned to General Electric and subjected to a variety of non-destructive, and destructive, inspections. This evaluation was conducted under the surveillance and direction of the NTSB Metallurgical Subgroup. An approved workscope, specific to each disk serial number was carried out. The results of which are listed below.

Fan Disk Serial No. MPO 00388 - This disk contained an ultrasonic indication (per current field shop procedures for immersion ultrasonic inspection of fan disks). This indication was in the web area of the disk, and there were macroetch indications in the bore and web area coincident with the ultrasonic indication. Macroetch indications were also identified in the forward side of the disk, extending from other web and bore indications on the aft face near the spacer ann. Metallurgical evaluation of the ultrasonic indication revealed the presence of a Type I nitrogen stabilized hard alpha material inclusion which had been introduced during the melting of the ingot. The area containing the Type I hard alpha inclusions displayed multiple, independent small cracks oriented in various directions.

No evidence of fatigue crack propagation from the Type I hard alpha inclusion was found. The macroetch indications, visible as dark stains on the BEA'd (Blue Etch Anodized) surface, have been determined to be areas similar to Type II "high aluminum" segregates within the disk.

Fluorescent Penetration Inspection (FPI) of the disk did not reveal rejectable indications. Bulk chemical analysis of this disk conformed to the material specification limits.

Fan Disk Serial No. MPO 00382 - This disk contained two macroetch indications. These were dark and light BEA stains typical of chemical segregation in the spacer arm flange area of the disk. Metallurgical investigation of both indications revealed the microstructure within these areas was acceptable per the applicable material specification. The chemical analysis of this disk showed that it conformed to the material specification limits.

Fan Disk Serial No. MPO 00384 - This disk was found acceptable per FPI and ultrasonic inspections. BEA inspection indicated areas located on three adjacent disk posts which were initially classified as possibly overheated microstructure. The bulk chemical analysis of this disk conformed to the material specification limits.

pan Disk Serial No. MPO 00386 - This disk was destructively evaluated to investigate non-rejectable ultrasonic indications located near the forward face of the disk bore. Metallographic evaluation of two separate bore regions which contained multiple non-rejectable ultrasonic indications did not reveal any evidence of a material anomaly as the cause for the ultrasonic results. The disk was judged to have been acceptable per FPI, ultrasonic and macroetch inspections. Bulk chemical analysis of this disk conformed to the material specification limits.

pan Disk Serial No. MPO 00383 - This disk was acceptable per FPI, ultrasonic and macroetch inspections. The bulk chemical analysis of this disk conformed to the material specification limits.

pan Disk Serial No. MPO 00387 - This disk was acceptable per FPI, ultrasonic and macroetch inspections. The bulk chemical analysis of this disk conformed to the material specification limits.

SECTION 3, BACKGROUND

TITANIUM PERSPECTIVE

Titanium is exceptionally resistant to corrosion in a very wide range of natural and other environments. This is the direct result of the strong affinity of the metal for oxygen, and the remarkable chemical stability and corrosion resistance of the metal oxide once formed. Titanium very rapidly acquires a tenacious oxide film when exposed to air or other oxidizing environments. The invisible film, less than a millionth of an inch thick, consists of a tetragonal crystal form of titanium dioxide, and acts as a very effective barrier against corrosion of the underlying metal. The film is self-healing and re-forms almost instantaneously if damaged.

This, along with its very high strength-to-weight ratio and light weight (562 of the weight of steel) accounts for its ever increasing usage and range of applications. At temperatures above 1000°F, however, titanium is a highly reactive metal which aggressively combines with atmospheric oxygen and nitrogen. Since titanium oxides and nitrides produce Type I hard alpha defects in the metal matrix, it is necessary to work in a vacuum or protective inert-gas atmosphere during large portions of the elemental titanium refining procedure (i.e. sponge production) and the titanium alloy consolidation and homogenization procedure (i.e. ingot production).

Titanium is an allotropic metal which can exist in two crystal forms, either a hexagonal close-packed (HCP) or a body-centered cubic (BCC) crystal'structure. The hexagonal close-packed structure is designated the alpha phase and the body-centered cubic structure is called the beta phase. Pure titanium takes the hexagonal close-packed crystal structure below 1620°F and the body-centered cubic crystal structure above this temperature which is called the phase transformation temperature or the beta transus temperature. The phase content forms the basis for classification of titanium alloys as alpha, alpha-beta, or beta types.

The addition of common alloying elements to pure titanium tends to change the temperature at which the phase transformation occurs and the amount of each phase present. Alloy additions to titanium therefore promote retention of a particular crystal form above or below the phase transformation temperature of pure titanium. Alpha stabilizers are elements that tend to retain the alpha phase or HCP structure to higher temperatures whereas beta stabilizers tend to retain the beta phase or BCC structure to lower temperatures.

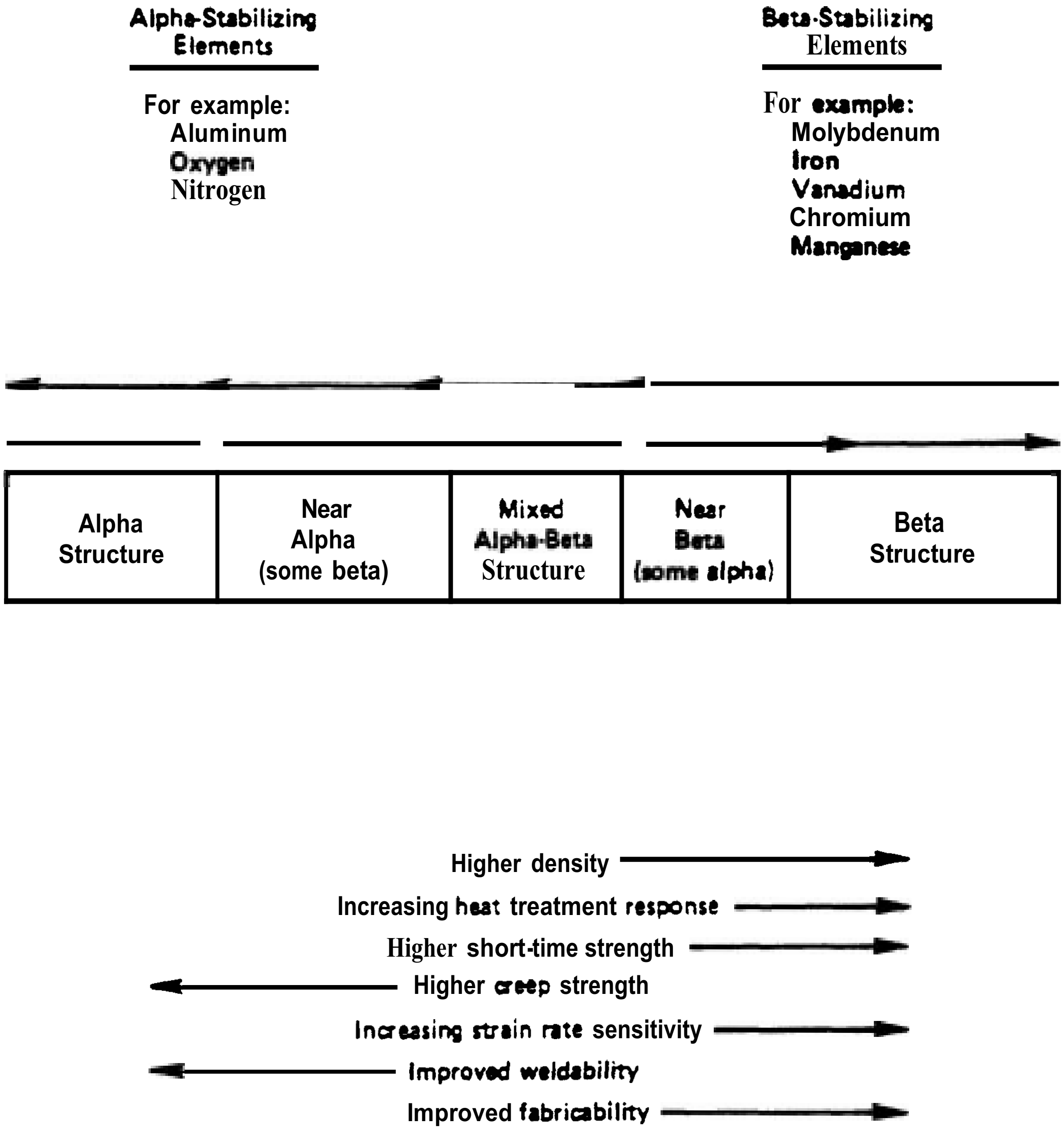
Alloying elements may go into solid solution in a metal either substitutionally or interstitially. A substitutional element is one with an atom size similar to the solvent (in this case, titanium) where the alloying atoms replace the titanium atoms in the crystal lattice. An interstitial element has relatively small atoms compared to those of the solvent and the alloying atoms assume positions between the titanium atoms in the crystal lattice. Alpha stabilizers of the substitutional type are aluminum, gallium, and germanium; interstitial stabilizers are oxygen, nitrogen, and carbon. Some beta stabilizers are vanadium, molybdenum, tantalum, columbium, nickel, copper, and silicon.

The most common turbofan-engine fan disk material is a titanium base alloy known as Ti 6-4 or Ti-6Al-4V which has a nominal chemical composition of 6% aluminum, 48 vanadium, and the balance being titanium. (This is also the material of the Sioux City fan disk.) The aluminum acts as an alpha stabilizer and the vanadium acts as a beta stabilizer, so in this material, both the alpha and beta phases exist below the beta transus temperature. Thus, the Ti-6Al-4V normal structure is a mixture of alpha and beta phases in a matrix, and the alloy is classified as an alpha-beta type titanium alloy.

Some other important titanium base alloys used in engine disks are:

COMMON NAME	CHEMICAL COMPOSITION	ALLOY TYPE
Ti 6-2-4-2	Ti-6Al-2Sn-4Zr-2Mo	Near a
Ti 6-2-4-6	Ti-6Al-2Sn-4Zr-6Mo	α-β
Ti 8-1-1	Ti-8Al-1V-1Mo	Near α
Ti 17 (17% alloy content)	Ti-5Al-4Cr-4Mo-2Sn-2Zr	α-β
Ti 5331s	Ti-5.5Al-3.5Sn-3Zr-1Nb	Near α
IMI 834	Ti-5.8Al-4Sn-3.5Zr-.7Nb-.5Mo-.3Si	Near a

Figure 3.C.1 shows some schematic relationships between alloy element additives and various material properties of titanium-base alloys.



SCHEMATIC RELATIONSHIPS: TITANIUM ALLOYING EFFECTS ON STRUCTURE AND SELECTED ALLOY CHARACTERISTICS.

FIGURE 3.C.1

SEGREGATION IN TITANIUM

Chemical element and phase segregation in titanium ingot must be stringently controlled because it leads to several different types of imperfections that cannot be readily eliminated by homogenizing heat treatments or combinations of heat treatment and primary mill (billet) processing.

Type I imperfections, also called "high interstitial defects", are regions of interstitially stabilized alpha phase that have substantially higher hardness and lower ductility than the surrounding material, and also exhibit a higher beta transus temperature. They arise from *very* high nitrogen or oxygen concentrations, often referred to as refractory titanium oxide, titanium nitride, or complex oxynitride particles in sponge, master alloy, or revert. During material processing, these refractory particles might become partially or totally diffused, dissolved, and/or deformed.

Figure 3.D.1 shows two examples of microstructures. The top photo shows a large spongy-appearing void, microcracked and demarcated alpha case, and enlarged alpha stabilized grains. Type I imperfections frequently, but not always, are associated with voids or cracks. The bottom photo shows a small void, no microcracks nor a rapid,;. changing microstructure. The examples were selected to illustrate the diversity of Type I imperfections in appearance and accompanying features. If carefully examined, the microstructure and chemistries of Type I defects often indicate the manufacturing operation which created the imperfection.

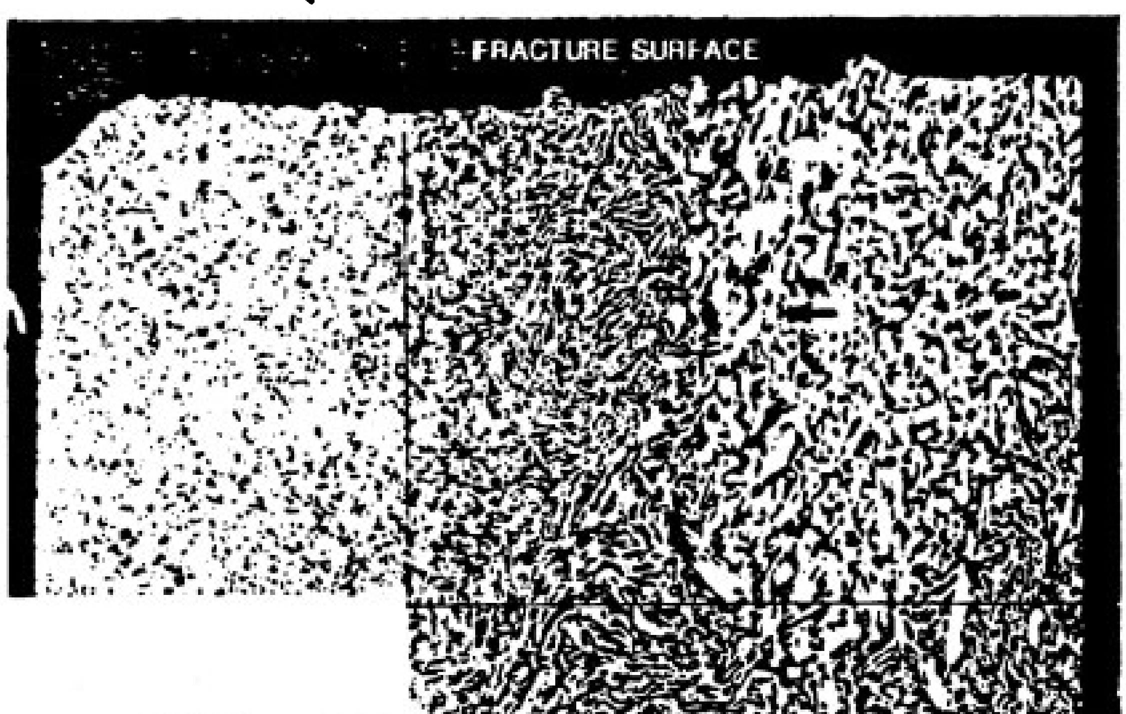
Although Type I imperfections sometimes are referred to as "low density inclusions", they can be of higher density than is normal for the alloy. But this term is used to differentiate them from HDI's or high density inclusions (see Definitions section).

Type II imperfections, sometimes called "high-aluminum defects", are abnormally stabilized alpha-phase areas that may extend across several beta grains. Type 11 imperfections are caused by segregation of metallic alpha stabilizers, such as aluminum, and contain an excessively high proportion of primary alpha having a microhardness only slightly higher than that of the adjacent matrix. Type II imperfections sometimes are accompanied by adjacent stringers of beta, areas low in both aluminum content and hardness. This condition is generally associated with closed solidification pipe or drop-in (Refer to Discussion section: Ingot). This report Will include both alpha and beta segregation as a Type II imperfection. Examples of alpha and beta segregation are shown in Figure 3.D.2.

75x

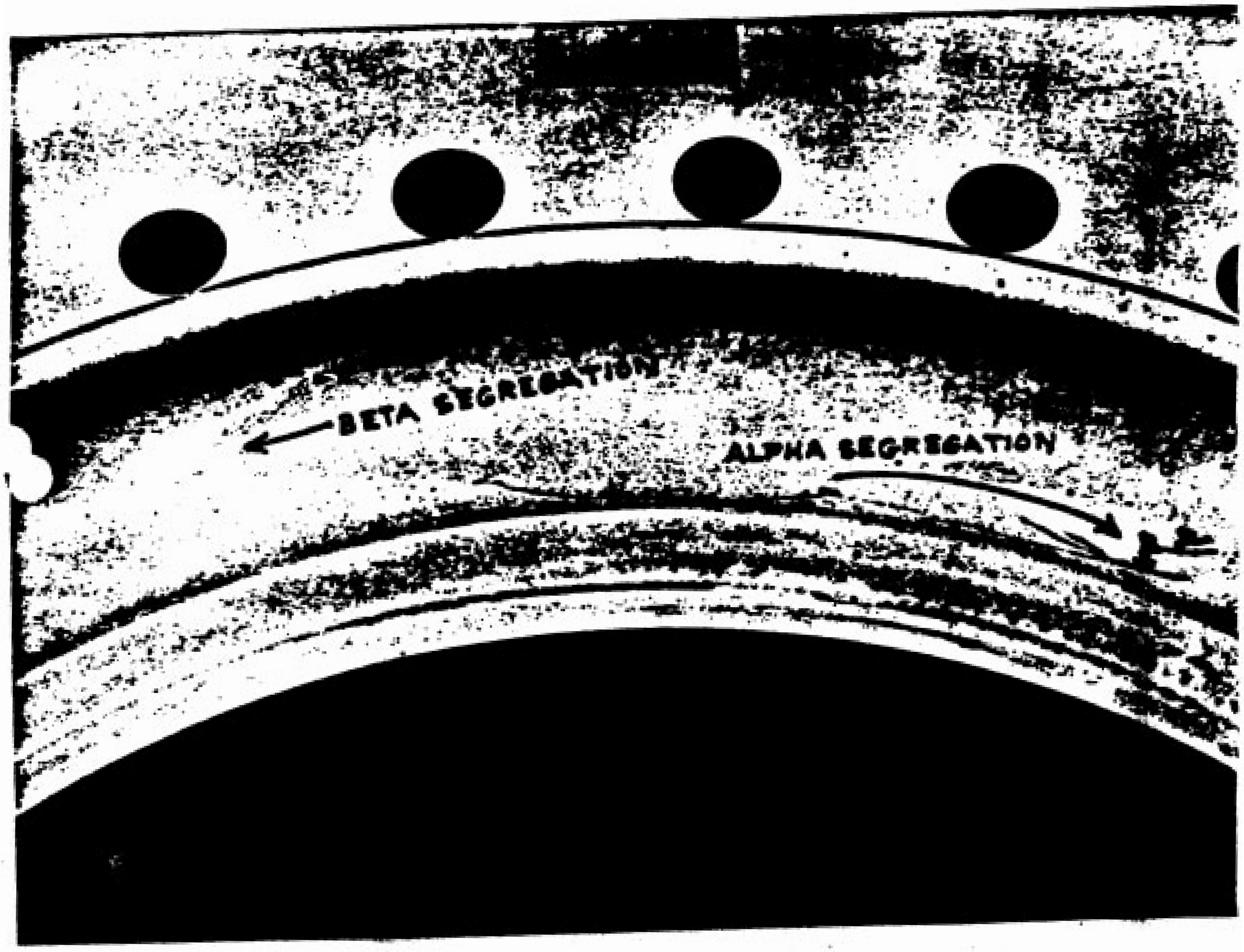
Photomicrograph shows Type I defect with voids surrounded by a thick microcracked layer of stabilized alpha or alpha case. This rapid change of microstructure between the alpha case and surrounding enlargedalpha grains indicates that this imperfection was created by burnt sponge. Arrows denote spongy-appearing material.

FIGURE 3.D.1



50X

Photomicrograph shows Type I defect showing slow gradation of alpha stabilized microstructure surrounding a void (arrow) with no alpha case. These characteristics indicate that this microstructure was created by contaminated revert or weldment. No microcracking was indicated in this photo but did exist in other areas.



(1 X) Alpha and beta segregation

FIGURE 3.D.2

Beta flecks, another type of imperfection, are small regions of stabilized beta in material that has been alpha-beta processed and heat treated. In size, they are equal to or greater than prior beta grains. Beta flecks are either devoid of primary alpha or contain less than oome specified minimum level of primary alpha. They are caused by localized regions either abnormally high in beta-stabilizer content or abnormally low in alpha-stabilizer content. Beta flecks are attributed to microsegregation during solidification of ingots of alloys that contain strong beta otabilizero. They are most often found in products made from large-diameter ingots. Beta flecks also may be found in beta-lean alloys such as Ti-6Al-4V that have been heated to a temperature near the beta transus during processing.

SECTION 4

TITANIUM ROTATING COMPONENTS REVIEW TEAM

November 1, 1989

CHARTER

TITANIUM ROTATING COMPONENTS REVIEW TEAM

Federal Aviation Administration (FAA) review of the July 19,1989, United Airlines DC10-10/CF6-6 accident at Sioux City has resulted in concern about the process quality control procedures used in the manufacture of titanium alloy high energy rotating components of turbine engines.

Consequently, a Titanium Rotating Components Review Team has been formed, and is charged with providing advice to the Engine and Propeller Directorate concerning the adequacy of current efforts within the engine industry to ensure the safety of these high energy components.

It is expected that the review team will consider all pertinent design, manufacturing, quality control, and inspection procedures and techniques, used in the production of these life-limited components. Specifically, Type I hard alpha metallurgical defects are of concern, but any other probable sub-surface or surface, micro or macro, effects that can substantially jeopardize the safe operation of titanium rotating parts should be considered.

Since the rotating component lifing methodologies of the various engine manufacturers, may be correlated to account for these imperfections to a greater or lesser degree, the individual manufacturer's lifing methodology will also be within the purview of the team.

The Directorate desires recommendations for necessary improvements, if any, in FAA, manufacturer, or operator procedures whenever and wherever appropriate in the life cycle of these parts. This will involve an evaluation of the effectiveness, necessity, and viability of: multiple vacuum melting procedure, engineering and manufacturing surveillance, inspection techniques, mid-life or repetitive inspections in service, and any other factors deemed appropriate in the prudent discretion of the review team.

The review team will conduct any necessary facility visits and submit any resulting recommendations within six months.

ENGINE AND PROPELLER DIRECTORATE
AIRCRAFT CERTIFICATION SERVICE
TITANIUM ROTATING COMPONENTS REVIEW TEAM

TEAM MEMBERS

ROBERT J. KOENIG (CHAIRMAN)	AEROSPACE ENGINEER, TURBOFAN & TURBOJET ENGINE SPECIALIST, AN€-110
JOSEPH G. COSTA	AEROSPACE ENGINEER, ENGINE CERTIFICATION8 ANM-140L
RAYMOND E. GONZALEZ	MANUFACTURING INSPECTION SPECIALPST, ANE-180
ROBERT E. GUYOTTE	MANAGER, ENGINE CERTIFICATION BRANCH, AN€-142
DANIEL P. SALVANO	ASST. MANAGER, AIRCRAFT ENGINEERING DIVISION, AIR-101
THOMAS SWIFT	NATIONAL RESOURCE SPECIALIST, FRACTURE MECHANICS, ANM-101N

SECTION 5, DISCUSSION

GENERAL

The descriptions given in the following sections of this Discussion are not intended to be all-inclusive; for example, discussion of certain details in the manufacturing process may have been skipped (e.g. heating and reheating to forging temperature) if they were considered unimportant to the Findings, Conclusions, or Recommendations.

TITANIUM SPONGE

Background

There are several chemical processing methods for winning titanium metal from the ore, rutile, which is essentially titanium dioxide, TiO_2. All of the methods developed to date are technically difficult and expensive because of the strong affinity of titanium for oxygen and other materials. Stringent requirements for maintaining the purity of reactants and control of processes must be imposed. The method which has become commercially viable worldwide is the reduction of the tetrachloride, $TiCl_4$, by an active metal, magnesium or sodium. (The tetrachloride is made available in an intermediate step wherein the oxide, TiO_2, is reduced using carbon and chlorine.)

Dr. W. J. Kroll developed the method using magnesium as the reducing agent as early as 1938 and refined the method in subsequent years. Sodium reduction of the tetrachloride (the Hunter process) also was being worked on at about the same time. Today, both magnesium and sodium reduction processes are used to supply the world's titanium metal (called sponge). The producing companies and countries are indicated in Table 1 which also gives plant production capacity.

The Titanium Review Team examined five methods of producing sponge for engine titanium rotors. These are the: (1) Kroll, (2) Hunter, (3) modified Kroll, (4) vacuum distillation finishing, and (5) electrolytic, processes. We visited the United States and Great Britain facilities shown in Table 1. Based on discussions held with two melters (ingot producers) who use or have used Japanese sponge made with vacuum distillation finishing, it was decided that a visit to the Japanese facilities was not necessary. The details and variations of each production facility's process are described in Volume 2 of this report, and include the chronological changes made to advance the state of the art.

Current Technology

Rutile for United States metal production is shipped in from abroad in a concentrate form suitable for chlorination in the two domestic operating plants. It is converted to the intermediate product, titanium tetrachloride, by a high-temperature reaction with chlorine in the presence of a reducing agent, carbon. The reactions are:

$$TiO_2 + 2Cl_2 + C \text{ ----> } TiCl_4 + CO_2 + \text{heat}$$

$$TiO_2 + 2Cl_2 + 2c \text{ ----> } TiCl_4 + 2CO + \text{heat}$$

TABLE 1: TITANIUM SPONGE METAL PRODUCTION FACILITIES AND ANNUAL PRODUCTION CAPACITIES

Plant and Location	Reducing Metal	Capacity Pounds/Year
United States		
Titanium Metals Corporation of America (Timet), Henderson, Nevada	Mg	28,000,000
RMI Company (Reactive Metals Inc.), Ashtabula, Ohio	Na	21,000,000
Oregon Metallurgical Corporation (Oremet), Albany, Oregon	Mg	13,000,000
Japan		
Osaka Titanium Co., Ltd. (Osaka), Amagasaki	Mg	12,000,000
Toho Titanium Co., Ltd. (Toho), Chigasaki Kangawa	Mg	9,200,000
Shin Kinyoku (affiliate of Japanese Chemical Concerns)	Na	3,600,000[a]
Great Britain		
Imperial Metal Industries, Ltd. (IMI) (Deeside Titanium, Ltd. (DTL))	Na	11,800,000[b]
Soviet Union		
Titanium-Magnesium Plant at Zaporozh'ye	Mg	11,000,000[e]
Titanium-Magnesium Plant at Berezniki	Mg	11,000,000[e]
Titanium-Magnesium Plant at Usk'Kamenogrosk	Mg	55,000,000[e]

(a) Constructed in early 1970's; never produced.
(b) Some sources indicate a capacity of about 7,000,000 pounds per year.
(e) Estimated.

These reactions are exothermic, the first producing 101,000 Btu per lb-mol at 1470°F; the second, 19,800 Btu per lb-mol. They are carried out at 1290 to 1830°F.

Since most metallic impurities in rutile are as easy to chlorinate as titanium, the product gases contain (in addition to the titanium tetrachloride) iron chloride, vanadyl trichloride, silicon tetrachloride, and other metal chlorides such as stannic chloride. Also, they contain other impurities including unreacted rutile and carbon dust, unreacted chlorine, phosgene, carbon dioxide, and carbon monoxide. The impure titanium tetrachloride is purified by gas/solid separators and distillation.

The degree of purity required of titanium tetrachloride for U.S. metal production is very high; an example is the maximum desired total oxygen content of 50 parts per million. The metallic impurities in the tetrachloride can be determined readily, but they are not as important in the final quality of the metal as the amounts of carbon, oxygen, and other nonmetallic impurities. The best test for the quality of tetrachloride is the grade of metal it will produce.

Magnesium Reduction (Kroll Process). The original large scale production of titanium metal in this country was based on the use of magnesium. The process depends on the high temperature chemical reaction:

$$TiCl_4^{(g)} + 2Mg^{(l)} \dashrightarrow Ti^{(s)} + 2MgCl_2^{(l)}$$

where: g = gas, l = liquid, s = solid.

According to this reaction, 3.961 pounds of titanium tetrachloride react with 1.015 pounds of magnesium to form 3.976 pounds of magnesium chloride and one pound of titanium metal. In practice, typically 1.25 pounds of magnesium are used for every pound of titanium won. Most of this can be recovered during the processing of the magnesium chloride by-product.

The reactor is a steel vessel with a flanged cover. The charge of magnesium, pickled free of surface oxides, is placed in the reactor and the lid is bolted or welded on. Magnesium also can be charged incrementally as the reaction progresses. The unit is transferred to a gas-fired furnace which has been evacuated and pressurized with helium or argon. It is heated to reaction temperature, and the titanium tetrachloride feed is started. The feed can be either liquid or vapor. Magnesium chloride is tapped off periodically as the reduction proceeds.

On completion of the reaction, a final tap is made and the vessel is removed from the furnace for cooling. When the vessel and contents cool to room temperature, the vessel is transferred to a dry room where the lid is removed and the contents are bored out. The chips of sponge titanium from the boring operation containing some magnesium chloride and the excess magnesium are transferred to the final step of separation from these impurities. Timet uses an automated acid leaching system to accomplish this separation.

The magnesium chloride tapped from the reaction pot is converted by electrolysis to magnesium metal plus chlorine. (The sodium chloride product from the sodium process is also electrolyzed.) In a metal reduction process (for example, $2Mg + TiCl_4 \text{ ----> } Ti + 2MgCl$) the by-product metal chloride is usually decomposed electrolyhcally and the product metal and chlorine recycled.

Sodium Reduction (Hunter Process). Sodium is used as a reducing agent in a cycle similar to that described for magnesium reduction. The process involves a two-stage reaction. First, pure titanium tetrachloride is introduced into a continuous reactor at 450°F where it combines with metallic sodium to form titanium dichloride and sodium chloride:

$$TiCl_4 + 2Na \text{ ----> } TiCl_2 + 2NaCl$$

The reaction vessel is equipped with an agitator and is kept under positive pressure with argon. The titanium dichloride and salt product which is free flowing is discharged with a screw conveyor into a sintering pot.

The sinter pot is charged with more sodium and then backfilled with argon after degassing. The incompletely reduced titanium dichloride and sodium react in the sinter pot to yield a complete stoichiometric reduction of the subhalide to the metal:

$$TiCl_2 + 2Na \text{ ----> } Ti + 2NaCl$$

The second reaction step is carried out at a controlled vessel temperature below 1900°F. As the titanium is won, it collects and agglomerates as fine particles which finally form a sponge. As the sponge mass forms in the sinter pot, it squeezes molten salt from the enveloping fiber network. After cooling, a column of sponge is surrounded and covered by sodium chloride.

The protective layer of salt and the mixture of titanium sponge and sodium chloride (spalt) is chipped from the pot using a remote-controlled pneumatic hammer. The spalt is then crushed to 3/8-inch size and titanium is separated from the impurities by an acid leaching process.

Both the Kroll and Hunter processes leave some volatiles and other impurities in the sponge. The volatile substances contaminate the protective atmosphere during welding of the sponge/alloy compacts, and result in ooot deposits on the walls of the vacuum welding chamber and the vacuum furnace melting chamber. In addition to the leaching process for the removal of impurities from sponge, a vacuum distillation process is available to accomplish purification.

Vacuum Distillation Finishing. Both Japanese and Soviet sponge products are finished by vacuum distillation techniques to provide high-purity titanium metal. The vacuum distillation finishing process may be carried out at 1650 to 1840°F. At 1650°F, the vapor pressure of magnesium is 90 mm Hg; of magnesium chloride, 7 mm. However, to insure good removal, the pressure should be less than 100 microns (0.1 mm) over the titanium sponge. The furnace for vacuum distillation of titanium sponge can be electric or gas fired. The shell of direct-fired furnaces must withstand the collapsing force of one atmosphere pressure at 1380°F. The sponge titanium is contained in an inner pot or basket. A section of the vessel extending out of the furnace, either above or below, acts as a condenser for the volatilized materials. Vacuum distillation is a more expensive process for purification than leaching. It has been estimated that vacuum distillation of domestic product would add from 25 to 30 cents per pound to the cost of producing sponge titanium (basis 1974).

Modified Kroll Process. The facility for producing sponge titanium at Oremet is of considerable interest because it differs somewhat from the conventional Kroll process of making sponge. The Oremet facility is sized to win metal in batch sizes up to 14,000 pounds instead of the usual 2,000 to 4,000 pound batch size. The product titanium sponge is not leached or vacuum distilled for removal of the excess reducing metal, magnesium, or the reaction product, magnesium chloride. Constituents of the reaction mass (still at temperature, of about 1800°F) are allowed to separate from the sponge by drainage. The solid sponge cake is supported by a grid which permits the liquid constituents of the reaction mass to pass. Further-separation is advanced to a completion point by a slow sweep of helium gas through the mass. The drainage and the helium sweep result in a good separation of the titanium from the residuals and volatiles and after a cooling period, the sponge cake can be removed from the vessel for mechanical chipping to a desired size for utilization.

Electrolytic (Direct) Reduction Process. This method of titanium metal winning is still not in production for turbine engine rotor parts, but is being or has been evaluated experimentally by more than one U.S. sponge manufacturer. The Titanium Review Team observed the electrolytic reduction process for titanium at RMI Company. This is a system manufactured by Ginatta Titanium in Turin, Italy.

Timet's work on the electrolytic titanium process and equipment has indicated that with properly sized equipment, about a 20 percent cost reduction over the Kroll process for making titanium, could be achieved. This advantage for the electrolytic process can be obtained in part because by-product chlorine from electrolysis can be used directly in the ore chlorinator to prepare $TiCl_4$. Titanium deposits at the cathode from the alkali chloride bath containing chlorides of titanium in solution. The bath may be operated at about 1560°F if it is of the type developed by Timet.

The present difficulty with the electrolytic process is that $TiCl_4$ is not very soluble in fused alkali chlorides. The lower chlorides, $TiCl_3$ and $TiCl_2$, are highly soluble, however, and tetrachloride feeds need to be reduced to the lower valence chlorides, preferably $TiCl_2$. In addition, it is necessary to prevent much reoxidation of the lower chlorides at the anode (where by-product chlorine is liberated) to inhibit $TiCl_4$ loss with the chlorine. Separations of anolyte and catholyte portions of the bath are therefore necessary and are accomplished by using diaphragms of various materials and preferred cell designs.

The Timet process utilizes the deposited titanium (on a metallic basket-type cathode) as a form of diaphragm. The Timet process is a batch type process in as much as titanium loaded cathodes require periodic replacement in order to harvest the titanium. (The Dow Chemical Company has reportedly developed another diaphragm design which might have long service life.) Titanium from electrolytic cells has been produced with a very low impurity content to yield once-melted ingots having a Brinell hardness of about 60. Standard production from Timet electrolytic cells is separated into the preferred grades of 90 Bhn and 75 Bhn titanium, which grades are offered for special purpose products.

Chemical Composition. Titanium sponge must meet stringent specifications for control of ingot composition. Most importantly, sponge must not contain hard, brittle, and refractory titanium oxide, titanium nitride, or complex titanium oxynitride particles that, if retained through subsequent melting operations, could act as crack initiation sites in the final product. Carbon, nitrogen, oxygen, silicon, and iron are commonly found as residual elements in sponge. There elements must be held to acceptably low levels because they raise the strength and lower the ductility of the final product.

<u>Much of the above information on titanium sponge</u> was condensed from "The Titanium Industry in the Mid-1970's", Report No. MCIC-75-26, dated June 1975, by Battelle's Columbus Laboratories, Metals and Ceramics Information Center. Based on

the visits (and data collected) by the Titanium Review Team, the processes are fundamentally the same today, and the explanatory information is still applicable.

The one area in the sponge production process which probably generated the most interest, discussion, and concern of the Review Team was the visual inspection of the product for defective material. This is done as a final operation, to classify the sponge as either premium quality or standard quality. It consists of searching primarily for burnt sponge particles which are discolored, from what should be dull gray, to bright blue and gold; and which contain titanium nitride and oxide which may lead to Type I defects in the final ingot.

The amount of visual inspection varies all the way from a 5% sample up to 110% of each sponge lot, depending on customer specification. Sponge particles, typically averaging 1/4 to 3/8 inch in size, are spread in a thin layer on a stationary or slowly moving conveyor belt for visual inspection.

Not every member of the Titanium Review Team could resolve his concern over inspecting anything less than 100% of a sponge lot. An improved comfort level, with the sponge visual inspections witnessed at all of the producers, was obtained once the sampling process was observed and understood.

We saw that a continuous sample is taken for visual inspection, meaning that sponge particles are continuously and randomly, mechanically shunted aside (to form the sample) as the entire sponge lot flows through a narrow constriction after having been thoroughly mixed. In this way, a sample is taken from every elemental volume in the bin: top, middle, bottom, and everywhere between. Since this results in literally hundreds of thousands of sponge particles in the sample that will be 100% visually inspected, it is the equivalent of a very large sample (i.e. hundreds of thousands of sponge particles actually viewed),

The entire sponge lot weighing thousands of pounds is downgraded to standard quality titanium if any discolored (burnt) particles are found to contain more than about 0.51 nitrogen by chemical analysis; and if so, the lot could not be used for engine rotor, major structural parts. Therefore, this type of visual sampling inspection for defective material may (or may not) be adequate for the purpose, in this kind of product. Thus, it is recommended that the Jet Engine Titanium Quality Committee (JET QC) consider this issue, and develop a uniform position to be approved by the FAA.

REVERT

The use of recycled scrap has historically been an important source of metallic raw materials in many industries. The generation and recycling of titanium scrap, also referred to as revert, is especially important because of the difficulty and expense involved in obtaining pure titanium from its ores. Effective use of scrap has been a key issue in the attempt to control ingot costs. Figure 5.C.1 illustrates the general upward trend in scrap utilization during the period 1962-1986.

Titanium scrap is generated in both the production of the basic alloy as well as user conversion of sponge or ingot and manufacture of end items from mill products. Scrap can be categorized according to size:

1. Bulk weldables weighing five or more pounds,

2. Feedstock with dimensions of 1 to 3 inches, and

3. Machine chips or turnings having bulk densities in the range of 10 to 50 pounds per cubic feet.

Bulk weldables can be easily fabricated into an electrode and then remelted in a vacuum arc remelt *(VAR)* furnace; while feedstock can be consolidated in either a non-consumable electrode, or a plasma, furnace. The last form of scrap, machine chips, is not suited for direct melting by conventional methods, without additional processing and consequent increased costs.

The large quantities' of recoverable titanium scrap that becomes available each year can be used in three ways:

1. Recycled into new titanium ingot or into castings,

2. Recycled into the production of steel or aluminum metal, or

3. Resold for conversion into non-critical titanium end items.

The factors determining the end use are fairly complicated but involve scrap pedigree, cleanliness, form, quality, availability, and demand for the related end use commodity. A description of some of the factors and end uses follows.

There are at least thirty different titanium alloys and grades that are used commercially although no more than half a dozen constitute the bulk of the titanium used. Since an alloy scrap

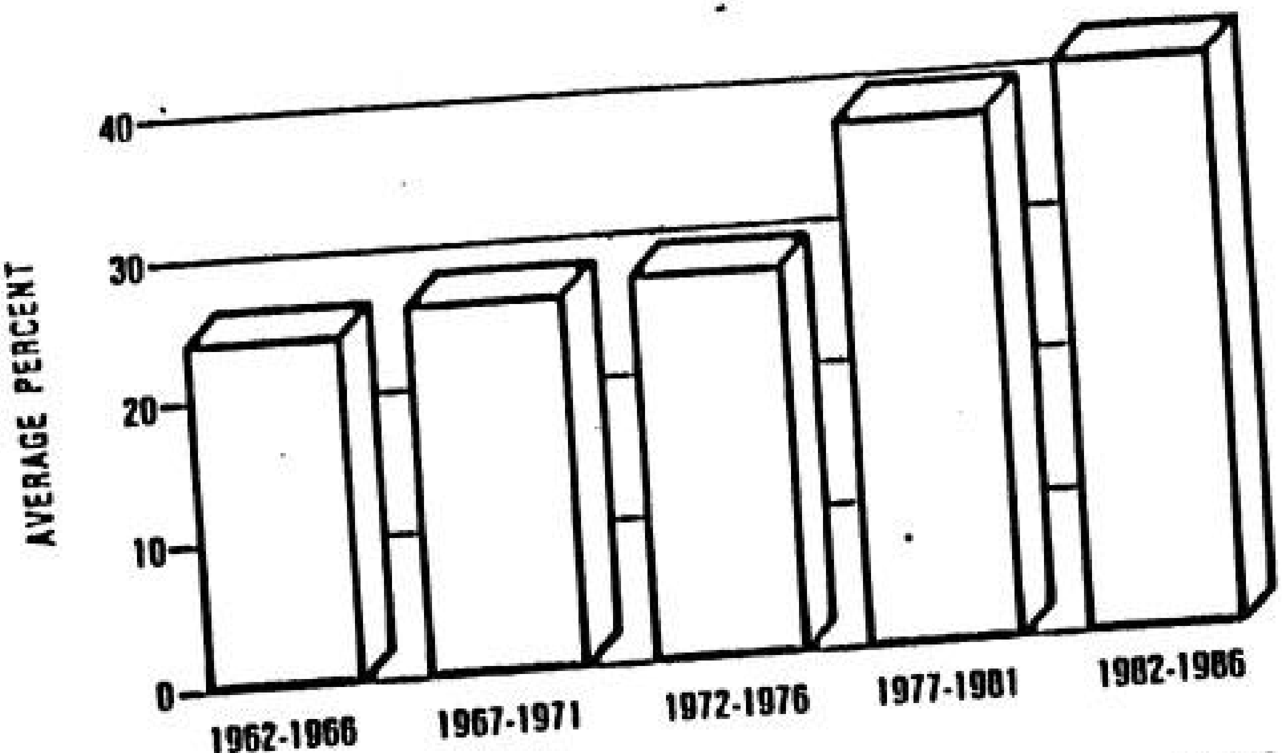


Figure 5.C.1 Because of favorable cost, scrap utilization has increased. Turning and machining chips, at even lower cost, are not as widely used due to quality issues

with constituents A plus B may be undesirable for an end use wherein only constituents C plus D may be tolerated, etc., the composition and pedigree of titanium scrap must be determinable, for scrap to have the highest value. Therefore, all producers of scrap desiring its high reclamation value, maintain alloy and grade identification and separation. Separation of titanium scrap from non-titanium scrap is especially important. The many producers of scrap have developed the art of scrap segregation to various degrees relative to the economics of their operations. The titanium producers, for example, take special care in maintaining the identification of their in-house scrap so that it may be recycled into new ingot. At the other extreme, some fabricators that turn mill products into finished parts claim that the problem of maintaining scrap pedigree is an uneconomical operation and prefer to devote their resources to their prime business. Scrap from such shops may be upgraded by dealers who have worked out identification and separation procedures.

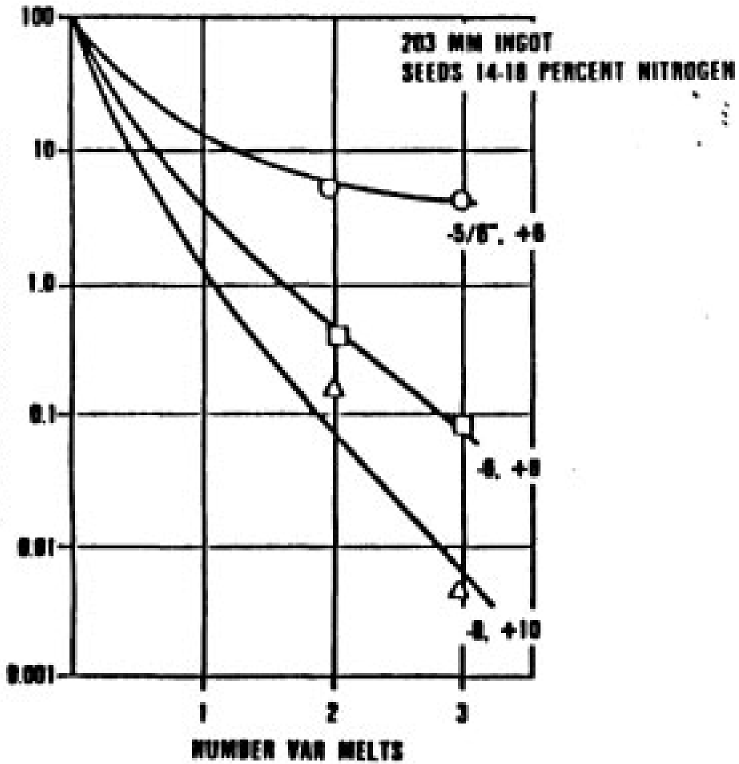
The cleanliness of scrap is of utmost importance to the titanium producers intending to recycle scrap into ingot. Contaminants ranging from lubricants and surface oxidation to broken bits of tool edges, are fairly common in scrap produced by the manufacturers of end products, but less common in titanium producer scrap. As might be expected, chips and turnings have a greater quality problem with respect to entrapped contaminants than massive scrap. Nevertheless, producers for processing chips (cleaning and segregating foreign materials) have developed to the point where even moderately contaminated scrap can be profitably recycled.

The producers of titanium ingot are reluctant to accept the risks involved in buying scrap of uncertain pedigree from the viewpoint of alloy content and quality. However, they can currently utilize some fairly low grade scrap after upgrading it in proprietary processes. After appropriate cleaning and screening, chips and turnings can be blended directly with fresh sponge and master alloy to prepare melting stock. Massive scrap can be directly consolidated into electrodes for melting, by welding. Some ingot producers prefer to use the chips, turnings, and massive scrap that they themselves generate, but utilize other than in-house scrap when scrap process and scrap qualities are suitable for their operations.

It is a general industry standard that titanium used to manufacture fracture-critical parts (i.e. disks, shafts, spools, etc.) for turbine engines, use the highest specification requirements, known as premium grade or rotating grade. This survey of the industry indicates that most engine manufacturer specifications do not have criteria on the use of scrap.

The two predominant types of scrap in use are bulk weldables and chips. Both types of scrap are susceptible to high density exogenous inclusions (HDI's) and low density inclusions (LDI's).

The fabrication of bulk weldables into an electrode may generate HDI's and LDI's. The enfoliated ends of billets (generated during conversion from ingot) may contain LDI's. Recent investigation by several titanium companies, sponsored by the government, indicated that the survival of a particular LDI in a melt is size and time dependent. See Figure 5.C.2. This Figure shows that triple VAR is superior to double VAR in dissolving seeded nitride defects.



PARTICLE SHAPE	PARTICLE SIZE	TIME FOR COMRCTC DISSOLUTION
SPHERICAL	$r \propto (r_o^3 - At)^{1/3}$	$T_c \propto Ar_o^3$
CYLINDRICAL	$r \propto (r_o^2 - Bt)^{1/2}$	$T_c \propto Br_o^2$
FLAKE	$y \propto (y_o - Ct)$	$T_c \propto Cy_o$

Y_o

Figure Survival of high nitrogen seeds in small VAR Ingot is strongly size dependent and is reduced by additional melt steps. US. Pat 4,678,506.

FIGURE 5.C.2

TITANIUM INGOT

Titanium base alloys used in the manufacture of engine high energy rotating components have historically been sourced in double- and triple-melted titanium alloy ingots processed in an electric arc furnace under vacuum, a process known as: multiple, consumable-electrode vacuum arc melting, or vacuum arc remelting (VAR). More recently, cold hearth melting techniques have been developed for the production of titanium ingot. However, the limits of cold hearth applied technology require cold hearth melted ingots to be remelted by the conventional consumable-electrode vacuum melt (i.e. VAR) process to achieve the specified chemistry.

The consumable electrode process of ingot production consists of consolidating chemically balanced charges of titanium sponge, master alloy, and in some cases, titanium chips from revert material, into compacts (bricks). Compacts are formed by mechanically compressing the molded, blended material under pressure. The compact's size and weight are dependent on the melters' geometric design and compacting machine capacity, and typically range from 70 to 350 pounds. The addition of alloying elements such as aluminum and vanadium (Ti-6Al-4V) to the titanium sponge has an important effect in achieving the desired physical and mechanical properties of the titanium product. The purity of these alloying elements is as important as the purity of the titanium sponge and must be controlled to avoid contamination with undesireable residual elements. Stringent process controls have been implemented to ensure that the presence of undesirable residual elements that can form high density inclusions, ,have been minimized. These in-process controls have been effective in reducing the probability of incurring high density inclusions in the final titanium product.

The consumable electrode (see Figure 5.D.1) is formed by assembling compacts on a holding fixture (armature) and welding the compacts together for electrode strength. The holding fixture is removed and an attachment stub is welded in place at one end of the compact assembly to provide retention capability in the vacuum arc furnace. Consumable electrodes may also be fabricated from bulk weldable solids obtained from revert material. Process controls have been implemented to ensure the cleanliness of welds in order to reduce the probability of introducing low density inclusions into the ingot. Welding in a vacuum chamber in a protective inert-gas atmosphere, together with monitoring of the mechanical systems for system failures which could introduce interstitial elements (carbon, oxygen, and nitrogen), have reduced the potential for ingot contamination.

The electrode is then transferred to the consumable vacuum arc remelt furnace (see Figure 5.D.2). The melting process is

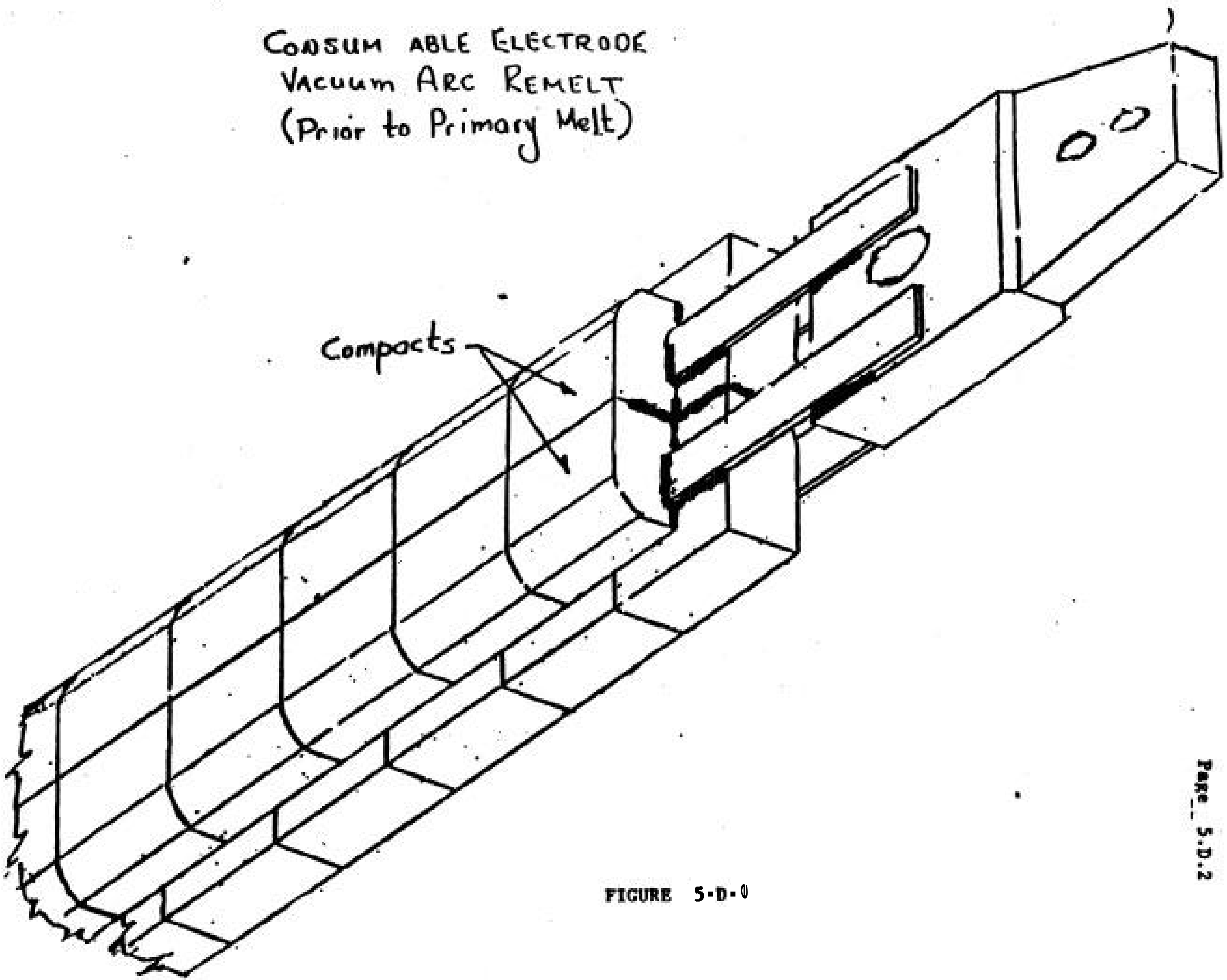
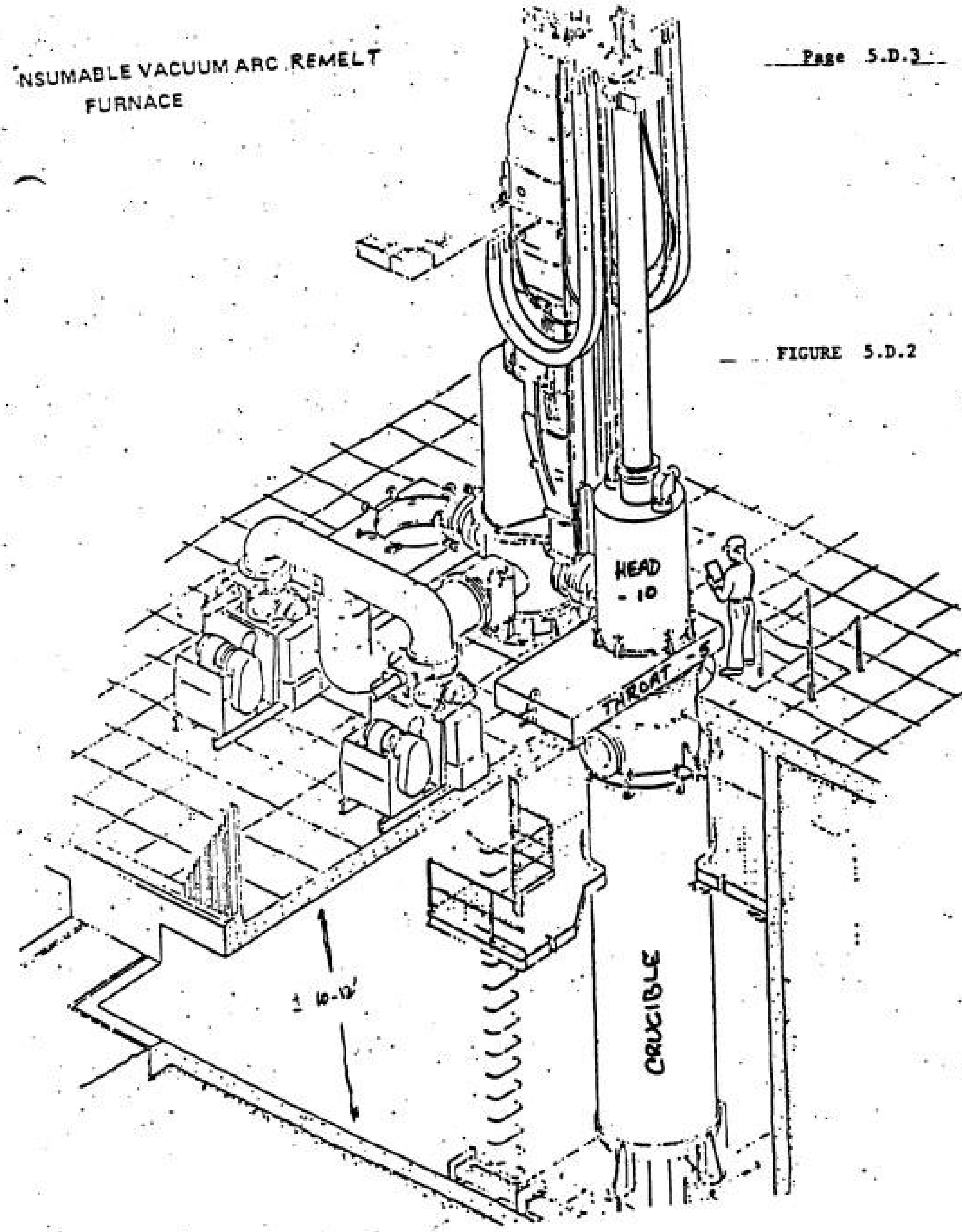

CONSUM ABLE ELECTRODE
VACUUM ARC REMELT
(Prior to Primary Melt)
Compacts

FIGURE 5-D-0

NSUMABLE VACUUM ARC REMELT FURNACE

FIGURE 5.D.2



initiated by striking an electric arc from the bottom of the electrode to the bottom of the receiving water-cooled copper crucible. Molten titanium from the electrode forms in a pool in the ingot crucible. The electrode is consumed during this process with the exception of the attachment stub end. Potential sources of low density inclusions are listed in Table 1.

Condition	Primary	Secondary	Tertiary
Furnace cleanliness	a	a	a
Vacuum leaks	a	a	a
Water leaks	a	a	a
Drop in	a	a	a
Arc interruption	a	a	a
Electrode surface cleanliness	n/a	a	a

Low density inclusions containing nitrogen, carbon, or oxygen enriched aluminum, exhibit higher melting temperatures than the titanium or titanium alloy, particularly those containing nitrogen. The inclusions entering the molten pool from the contaminant source are swept away from the super heat area by convection currents and density separation. Nitrogen rich alpha inclusions are the most stable, least likely to melt or dissolve in the molten pool as a result of the short residence time in the liquidus-plus temperature zone of the molten pool, and are the most common type found in production material. It is therefore imperative that quality controls during the melt process, electrode fabrication, and selection of raw material stages be properly administered to prevent ingot contamination.

Two primary ingots are welded end to end to form the consumable electrode for the second-melt ingot and similarly two secondary ingots are welded together for the tertiary melt. Ingot surface cleanliness is important. Several methods were observed by the Team, from hand grinding to machining. To prevent contamination of subsequent melts, it is imperative to remove surface scale down to clean, sound metal prior to remelting. Titanium is currently produced in the following size ingots:

Diameter (inches)	Weight (pounds)
28	7,000
32	10,000
34	14,000
36	20,000

Multiple melting of ingots provides a better quality of titanium and titanium alloy material, by providing additional exposure to the liquidus-plus temperature for melting or dissolution of low density inclusions. Triple vacuum melted material should be the minimum standard for titanium and titanium alloy premium grade material for use in rotating high-energy engine components.

The engine manufacturers and the titanium ingot producers have embarked on "clean melt" cold hearth programs for the production of titanium and titanium alloys. Two methods, electron beam melting and plasma arc melting of titanium raw material stock, have been developed. Figures 5.D.3 and 5.D.4 depict the two processes being developed for titanium production. The development of the cold hearth process provides a means of controlling the residence time of a contaminant in the liquidus-plus temperature zone to allow for melting or dissolution of low density inclusions. High density inclusions settle into the scull at the bottom of the melt pan, and are trapped in the semi-solidified material adjacent to the water-cooled jacket. Currently, ingots produced by this process must be vacuum arc remelted to achieve a homogeneous chemistry. The titanium industry should continue its efforts to develop more-nearly defect-free titanium alloy material for engine critical components.

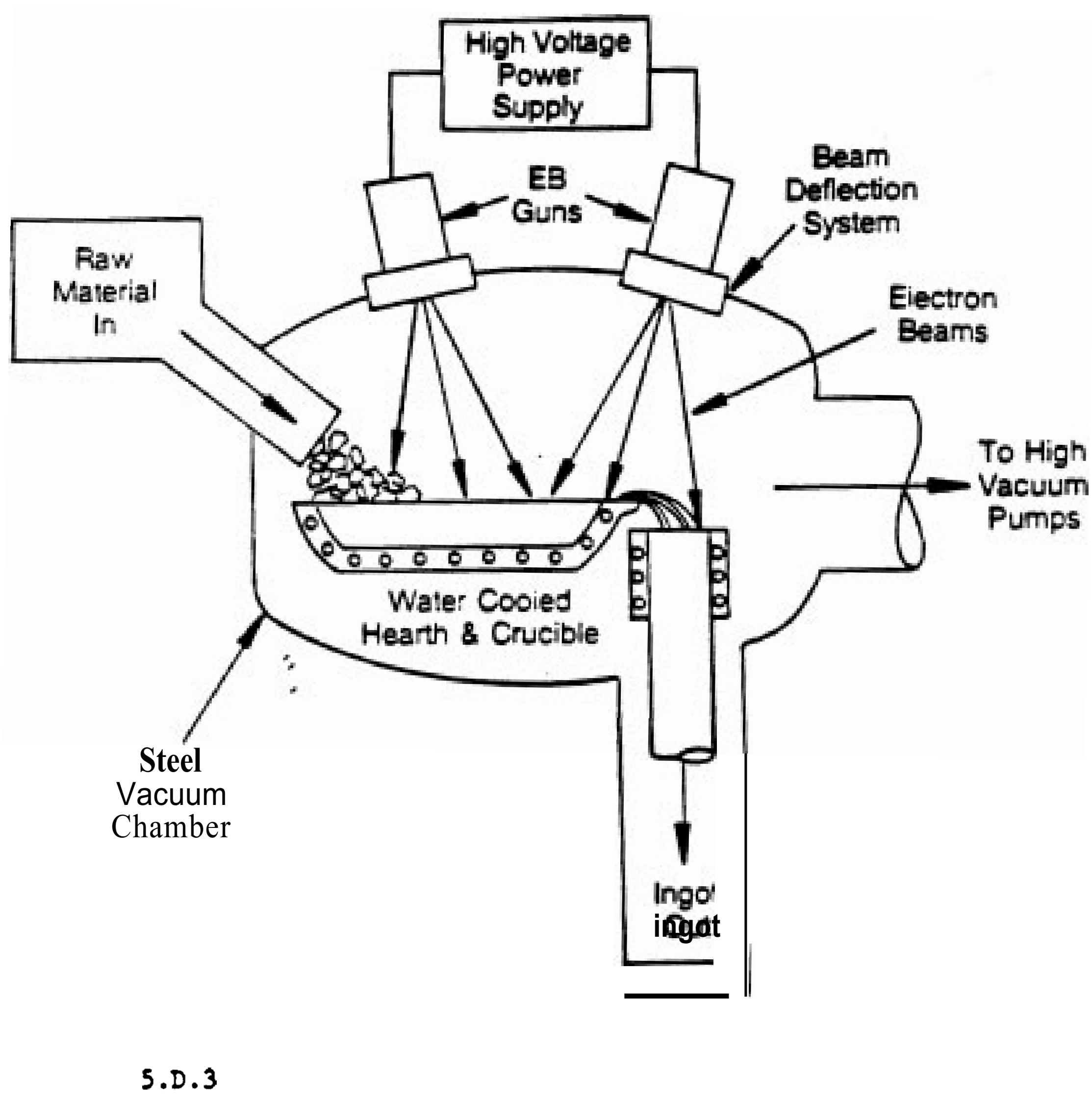


Figure 5.D.3 - Schematic drawing of electron beam cold hearth refining furnace showing material flow.

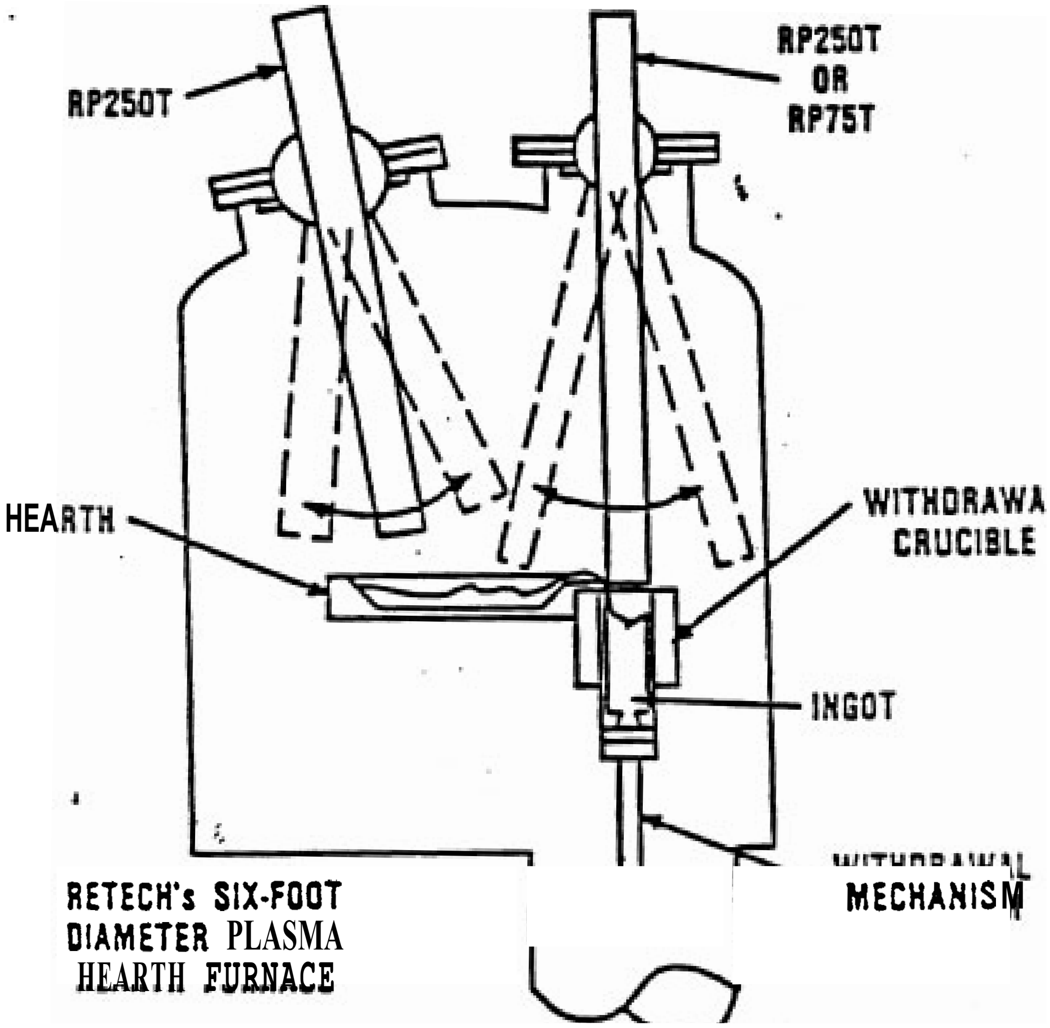


Figure 5.D.4 Plasma Arc - cold hearth melting of scrap virgin materials is projected to reduce refractory defects.

BILLET

Ingots approximating 30 inches in diameter and 10 feet long are hot forged, downward in diameter while increasing proportionately in length, until the appropriate diameter for die forging of the disk is reached. The resulting material is termed "billet", and for turbine engine disks it is usually sized between 4.5 and 14 inches in diameter (after grinding or turning), depending on the size of the disk to be made from it. (Material less than or equal to 4.5 inches in diameter is called "bar" and is used in making blades, but no current commercial engine disks are small enough to be made from this size stock.) It is at this stage in the manufacturing process (i.e. the billet stage) that the material receives its first ultrasonic inspection.

Wrought (plastic) deformation of the ingot is critical in grain refinement, so much so, that some forgers first upset the ingot (hot press ends of ingot together to increase diameter), then perform the normal diametral forging operation, or will start forging with the largest diameter ingot possible. In any case? the final billet product has a carefully controlled metallurgical structure in accordance with purchaser specifications. A refined grain structure is directly relatable to better mechanical properties, and as importantly, improves the Ultrasonic inspectability of the material.

The billet manufacturer examines the microstructure, macrostructure, and material homogeneity by etch/visual and ultrasonic inspections. Macroetching and ultrasonic inspection of the billet ends which coincide with the ingot ends are important in eliminating mechanical working anomalies such as cracks or enfoliations and melt porosity such as pipe.

Improvements in the preparation and ultrasonic test procedure for billet were made in 1971 when automatic indexing and water immersion replaced hand-held contact inspection. Also, fine grind or billet turning replaced the rough "Mid-West" or longitudinal grind. Both process changes were viewed as significant in improving the inspectability of titanium billet; and the flat-bottomed hole (FBH) size, inspection acceptance standard has been improved over the years from 8/64 inch diameter.

The current industry ultrasonic inspection standard for all premium grade billet sizes (i.e. 4.5 to 14-inch diameter) is effectively the 3/64 inch diameter FBH. The industry capability is now such that the ultrasonic inspection standard can be further improved. The following levels are considered to be practicable: 1/64 inch diameter FBH for billet ≤ 5 inches, 2/64 FBH for billet > 5 but ≤ 10 inches, and (staying with) 3/64 FBH for billet > 10 inches.

There may be some question as to how good the billet inspection needs to be when the semi-finish-machined disks are later inspected to a 1/64 FBH (which is the case for most engine manufacturers). However, the uniform cylindrical shape of billet is the simplest configuration the material will ever be in for ultrasonic inspection, resulting in the sonic signal being relatively clear and uncomplicated (i.e. minimal scattering and no stray reflective signals from angled and intersecting surfaces as on the rectilinear disk). The Review Team found enough defects which made it all the way through the inspection process and into service, that we believe the manufacturing and quality control system needs to be tightened wherever reasonably possible.

The big disadvantage for ultrasonic inspection at the billet stage is the sometimes large diameter of the forging stock coupled with titanium's relatively large sonic attenuation. Also accompanying the large diameter billet, is a coarser grain structure (due to less forge working) which results in a "noisier" medium for ultrasound transmission.

Some engine manufacturers require instructive metallurgical confirmation of ultrasonic indications and documentation of defects, if they are confirmed, in a sonic report. Some also require that quarterly reports of the number of defects confirmed by destructive testing be sent to the engine manufacturers.

After reviewing many individual sonic investigation reports (Ref. Volume 2) and after discussions with the ingot converters (billet manufacturers) the Team found that the procedure of sectioning and successive grinding and polishing steps for locating the ultrasonic indication was acceptable. However, a detailed characterization of the defect and sonic signal documentation was not recorded. Even though many ingot converters did not submit, when requested, their sonic investigation reports to the Review Team, after discussion with these billet forging sources, it was concluded that their sonic reports were similar in the type of data recorded.

We saw no particular problems in this stage of manufacture, as far as the introduction of Type I and Type II defects is concerned, but the greater the plastic strain introduced in going from ingot to billet, the better the transmissivity of the material to ultrasound, and the less interference with a signal reflected from a defect.

DEFECT RATES

The apparent rate of Type I defect ocurrence (i.e. the number of defects found per million pounds of titanium melted) fluctuates significantly from year to year, and according to some data, decreases substantially as billet diameter increases. Although the industry average rate has improved over the years, it is still not significantly under about 1 Type I defect per million pounds of triple melted material (combining all billet diameters inspected).

This statistic, however, may be very misleading because it probably understates the real rate. There is no reason to believe that large diameter billet (e.g. 14-inch) has any fewer defects than medium diameter billet (e.g. 9-inch); yet according to some ultrasonic inspection results, only about 0.5 defects per million pounds were detected in 14-inch billet, while about 6 defects per million pounds were found in 9-inch billet. Since all billet diameters come from ingots which are manufactured in the same way, and since it is known that defects become more difficult to detect (ultrasonically) as the part thickness and grain coarseness increase, it seems reasonable to conclude that all billet sizes must have about the same number of defects per million pounds, and that the number of defects found in small size billet (i.e. ≤ 6-inch diameter) is indicative of that which is actually being produced in all billet made from triple VAR ingot.

The Titanium Review Team found some data that showed a Type I defect rate greater than 10 defects per million pounds in the small billet diameters. If this (i.e. 10) is representative of all titanium disk material, and the industry is only finding about 1 defect per million pounds, average, then apparently 9 defects per million pounds of ingot would be entering the disk forging process, undetected. Since there is about a 40% yield in going from ingot to disk forging, this would equate to about 1 defect in every 178 fan disk forgings. That is: 1,000,000 pounds X 40% yield + 250 pounds per fan disk + 9 defects = 178 disks per defect.

Ultrasonic inspections of semi-finish-machined disks and etch inspections of finished disks do not show anywhere near this rate of defects, even though the normal disk inspection standard (1/64 FBH) is tighter than the normal billet inspection standard (3/64 FBH). As an example of the apparent defect rate per disk, one engine manufacturer, in a production volume of thousands of titanium disks of various sizes, found 1 defect per 3,400 disks. Probably one major reason for this is that most defects are found near the axial centerline of the billet (within a circular zone of radius equal to 1/3 the billet radius, and centered on the

DEFECT RATES

The apparent rate of Type I defect ocurrence (i.e. the number of defects <u>found</u> per million pounds of titanium melted) fluctuates significantly from year to year, and according to some data, decreases substantially as billet diameter increases. Although the industry average rate has improved over the years, it is still not significantly under about 1 Type I defect per million pounds of triple melted material (combining all billet diameters inspected).

This statistic, however, may be very misleading because it probably understates the real rate. There is no reason to believe that large diameter billet (e.g. 14-inch) has any fewer defects than medium diameter billet (e.g. 9-inch); yet according to some ultrasonic inspection results, only about 0.5 defects per million pounds were detected in 14-inch billet, while about 6 defects per million pounds were found in 9-inch billet. Since all billet diameters come from ingots which are manufactured in the same way, and since it is known that defects become more difficult to detect (ultrasonically) as the part thickness and grain coarseness increase, it seems reasonable to conclude that all billet sizes must have about the same number of defects per million pounds, and that the number of defects found in small size billet (i.e. ≤ 6-inch diameter) is indicative of that which is actually being produced in all billet made from triple VAR ingot.

The Titanium Review Team found some data that showed a Type I defect rate greater than 10 defects per million pounds in the small billet diameters. If this (i.e. 10) is representative of all titanium disk material, and the industry is only finding about 1 defect per million pounds, average, then apparently 9 defects per million pounds of ingot would be entering the disk forging process, undetected. Since there is about a 40% yield in going from ingot to disk forging, this would equate to about 1 defect in every 178 fan disk forgings. That is: 1,000,000 pounds X 40% yield + 250 pounds per fan disk + 9 defects = 178 disks per defect.

Ultrasonic inspections of semi-finish-machined disks and etch inspections of finished disks do not show anywhere near this rate of defects, even though the normal disk inspection standard (1/64 FBH) is tighter than the normal billet inspection standard (3/64 FBH). As an example of the apparent defect rate per disk, one engine manufacturer, in a production volume of thousands of titanium disks of various sizes, found 1 defect per 3,400 disks. Probably one major reason for this is that most defects are found near the axial centerline of the billet (within a circular zone of radius equal to 1/3 the billet radius, and centered on the

FORGING

After passing ultrasonic inspection, billets (typically 12 feet long, more or less) are mechanically cut into short lengths (e.g. 1 foot) in preparation for closed-die forging into the disk shape. These short length pieces are termed multiples or "mults". Each mult is then heated and upset (in steps) along its axis (like a solid rivet), decreasing in length and expanding in diameter to fill the die cavity: After forging, the part is heat treated to the required final condition.

The forging is then semi-finish-machined to a mostly parallel-sided (i.e. orthogonal or rectilinear) disk shape that is about 1/8 inch outside the finish-machined contour. See Figure 5.G.1. This 1/8 inch of extra material, all around, is the so called "dead zone" which is not readily inspectable by ultrasonic (pulse/echo) methods, The extra material is left on so that the entire volume of the finish-machined contour can be ultrasonically examined for metallurgical defects.

The main purpose of closed-die forging is to control the grain flow and grain size to obtain a better combination of mechanical properties than exist in billet. Other methods used for forging titanium alloys include open-die, upset and roll forging, and ring rolling. By far the greatest tonnage of titanium alloy forging of disks is produced in closed dies. The use of one or more of these forging methods in conjunction with specific forging pressures and temperatures throughout a prescribed manufacturing sequence is important in developing a satisfactory degree of microstructural uniformity with acceptable mechanical properties in any given final shape of part. Other factors affecting microstructure and mechanical properties are cooling rates and subsequent heat treatments, chemistry (controlling absorbtion of oxygen, nitrogen, and particularly hydrogen), and uniform working of the entire forging.

In addition to controlling mechanical properties, the finished forging process also improves the transmissivity of titanium alloys to ultrasound. As discussed in the UT section, ultrasonic waves are easily attenuated in titanium material with coarse grain structure. On the other hand, some forgers have claimed that a forging that has received too much "strain energy" will scatter ultrasonic waves and reduce testing sensitivity. While improvements have been made in sonic shape inspectability (through grain structure refinement techniques), the absolute level of inspectability remains rather limited in comparison with other metals.

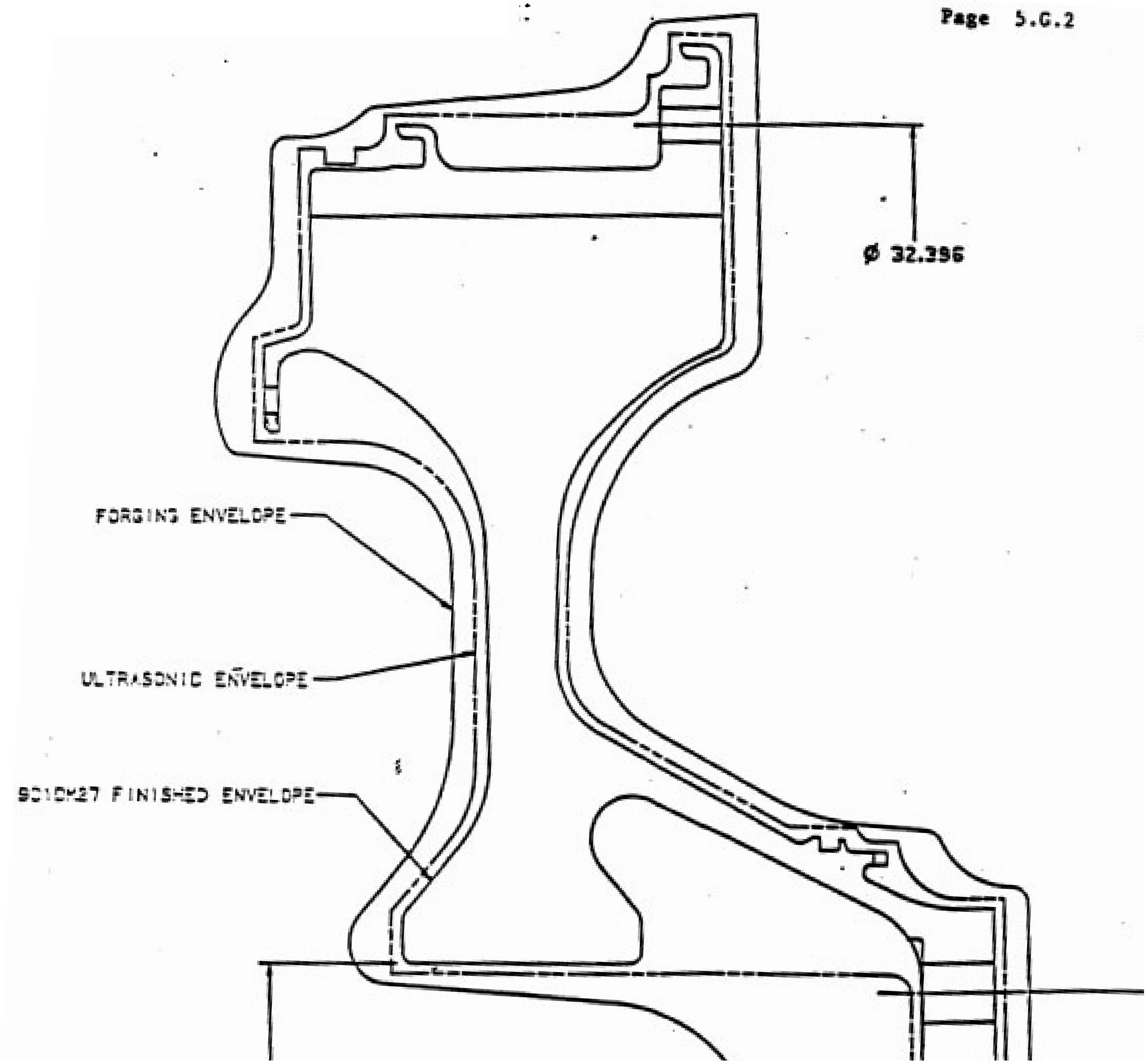


Figure 5.G.1: Forging contour, sonic (rectilinear) shape, and finish-machined contour or shape.

Since the finished forging and heat treating process is the last stage in the manufacturing process that will significantly affect mechanical properties and microstructure, it is essential that quality assurance be established and maintained. Each forger generates a documented process and quality control procedure which must be approved by the engine manufacturer. Furthermore, alterations to this procedure must also be approved by the engine producer.

In addition to the control & surveillance of equipment, flow instructions, and personnel training, the following destructive & non-destructive testing of forgings occur:

Destructive Testing

1. Mechanical properties testing
2. Metallographic examination
3. Chemistry analysis

Non-Destructive Testing

1. Immersion ultrasonic
2. Segregation etch
3. Fluorescent penetrant inspection

Most forgers are willing to perform all of the above tests, however, it is up to the engine manufacturer's drawing specification to call out the required testing and documentation.

Overall, the forging houses produce quality titanium disk forgings with properties that meet the engine manufacturer's specifications. The Team found no indications that the die forging operation significantly causes or contributes to the development of Type I or Type II defects.

The main area where significant improvement is possible is in the characterization (i.e. 3-dimensional measurement, chemical, physical, and/or mechanical properties determination, location in the disk, etc.) and reporting of defects found in the sonic shape. This information is needed (by the design engineer) in the form of statistical distributions in order to perform a proper Monte Carlo reliability simulation/analysis of disk burst probability resulting from metallukgical defects.

Some forging houses which ultrasonically test titanium forgings, are required to destructively confirm potential defect indications. As reported, there are many fewer defects found in the forging's sonic shape than found in billet. Nevertheless, the submittal of confirmation reports to the engine companies are not required.

After reviewing some of these reports, the Team finds that these reports aren't informative enough. (This subject is discussed more thoroughly in the Ultrasonic Inspection sub-section of Section 5.H of this report.) In addition, the sonic investigation reports do not include a traceability study which relates the defective material back to the ingot melting practice and its elemental constituents.

NON-DESTRUCTIVE INSPECTION

NDI techniques are used throughout the disk manufacturing process to identify, for purging, any defective material or parts, and as a good monitor for problems in manufacturing process control.

The main NDI methods used in the titanium disk manufacturing process are:

1. visual inspection of the titanium sponge (or granules),
2. chemical analysis of sponge samples,
3. chemical analysis of samples from the ingot,
4. immersion ultrasonic inspection of the billet,
5. etching of the billet for micro and macrostructure, and segregation,
6. immersion ultrasonic inspection of the forged, semi-finish-machined disk,
7. etch inspection of the disk for segregation and macrostructure, and
8. fluorescent penetrant inspection of the finish-machined disk.

FLUORESCENT PENETRANT INSPECTION

Liquid penetrant inspection is used to detect small discontinuities which cannot be easily found during simple visual inspection. The method depends on the ability of a highly penetrating liquid to seep, through capillary action, into any discontinuity in the material to which it is applied. It can only be used to detect surface defects, and subsurface defects that are open to the surface.

The penetrant inspection technique has been around for a long time. During the 19th century, railroad car axles were inspected using oil as the penetrant and talcum powder as the developer. Even in the early days of aviation, certain engine parts were inspected using oil as the penetrant and saw dust (cut to a specification) as the developer.

The liquid penetrant inspection process can be pictorially represented as shown in Figure 5.H.1. There are six critical steps in the penetrant inspection of a part:

1. Surface preparation - The part surface must be cleaned of all Contaminants (such as rust, scale, oil, etc.), paint, or plating to assure any defect is open to the surface of the bare material.

2. Penetrant application - A properly selected fluorescent or non-fluorescent penetrant is applied either over the entire part or at least one inch around a particular area to be investigated.

3. Removal of excess penetrant - Excess penetrant is removed to minimize the possibility of false indications.

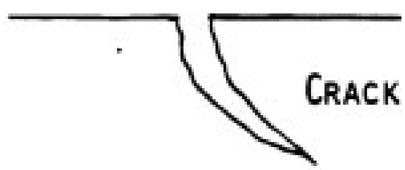
4. Developer application - The developer acts like a blotter and draws the penetrant out of any discontinuity and brings it to the surface. It also spreads out and amplifies the penetrant to make it more readily seen. Since the penetrant is diffused on the surface, the indication will be larger than the real discontinuity.

5. Inspection - A true indication occurs when penetrant bleeds back to the surface from a discontinuity.

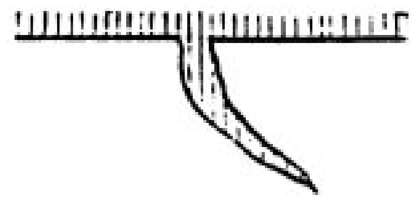
6. Post test cleaning - Remove residual developer and penetrant for return to service or additional inspection.

Until recently, it was believed that with proper process controls, fluorescent penetrant inspection (FPI) detection efficiencies comparable to the other NDI methods could be

LIQUID PENETRANT INSPECTION

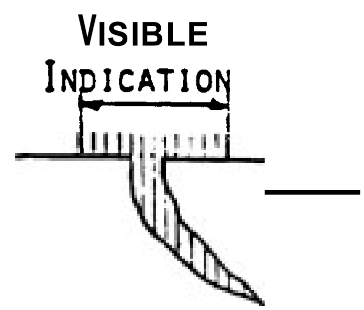


STEP 1. SURFACE PREPARATION



STEP 2. PENETRANT APPLIED TO SURFACE

STEP 3. EXCESS PENETRANT REMOVED FROM SURFACE



STEP 4. DEVELOPER APPLICATION DRAWS PENETRANT OUT OF DEFECT

ADVANTAGES

1. WIDE AREA COVERAGE
2. HIGH SENSITIVITY TO FINE DEFECTS

DISADVANTAGES

1. INSPECTION INDICATION QUALITATIVE
2. COMPLEX PROCESS, SUBJECT TO VARIATIONS
3. ONLY FOR SURFACE DEFECTS

FIGURE 5.H.1

maintained for crucial crack lengths usually encountered in engines. Figure 5.H.2 graphically shows the differences in detection efficiency of several inspection methods for crack lengths typically found in turbine engines. Data analysis from two typical airworthiness directives (AD's) have resulted in their being revised. The AD's were on turbofan engines from two manufacturers: one engine is a low bypass, air carrier engine with over 20 years service experience, and the other is a high bypass engine of the 25 ton thrust class. The AD's had several similarities:

1. In both cases, FPI was the primary inspection means;

2. The areas being inspected were of complex geometry. For one, the critical area was the embossment radius on a turbine disk, while the other was an inspection of compressor disk tie bolt holes;

3. The crack sizes used to determine the inspection limits were approximately the same; and

4. The required inspection programs did not work as originally predicted.

This last item and its correction became the FAA's immediate concern since disk failure continued after the AD's were issued. Both manufacturers, with the FAA, began intensive evaluation of the FPI inspection process, procedures, and capability. In both instances, the major findings agreed. The inspection method used, had sufficient detection sensitivity for cracks of the size expected, but could not register the indications with sufficient reliability. Figure 5.H.3 graphically shows this difference in inspection reliability.

Comparison of initial inspection data supplied by one of the manufacturers with subsequent reinspection data, showed approximately a 25% increase in the crack length required for a detection level of 90%. Past experience with airworthiness problems utilized the philosophy of determining a lower boundary on crack detection sensitivity and using this for developing the inspection program. The variation of detection capability, or the reliability of inspection, was not included. This variation was the prime factor for the continued failures. The FAA review of literature, current at the time, concerning NDI reliability indicated that this should not have been unexpected.

TYPICAL LABORATORY CAPABILITY
FOR VARIOUS ADT PROCESSES
(INCO 718 - CLEAN FIAT SPECIMENS)

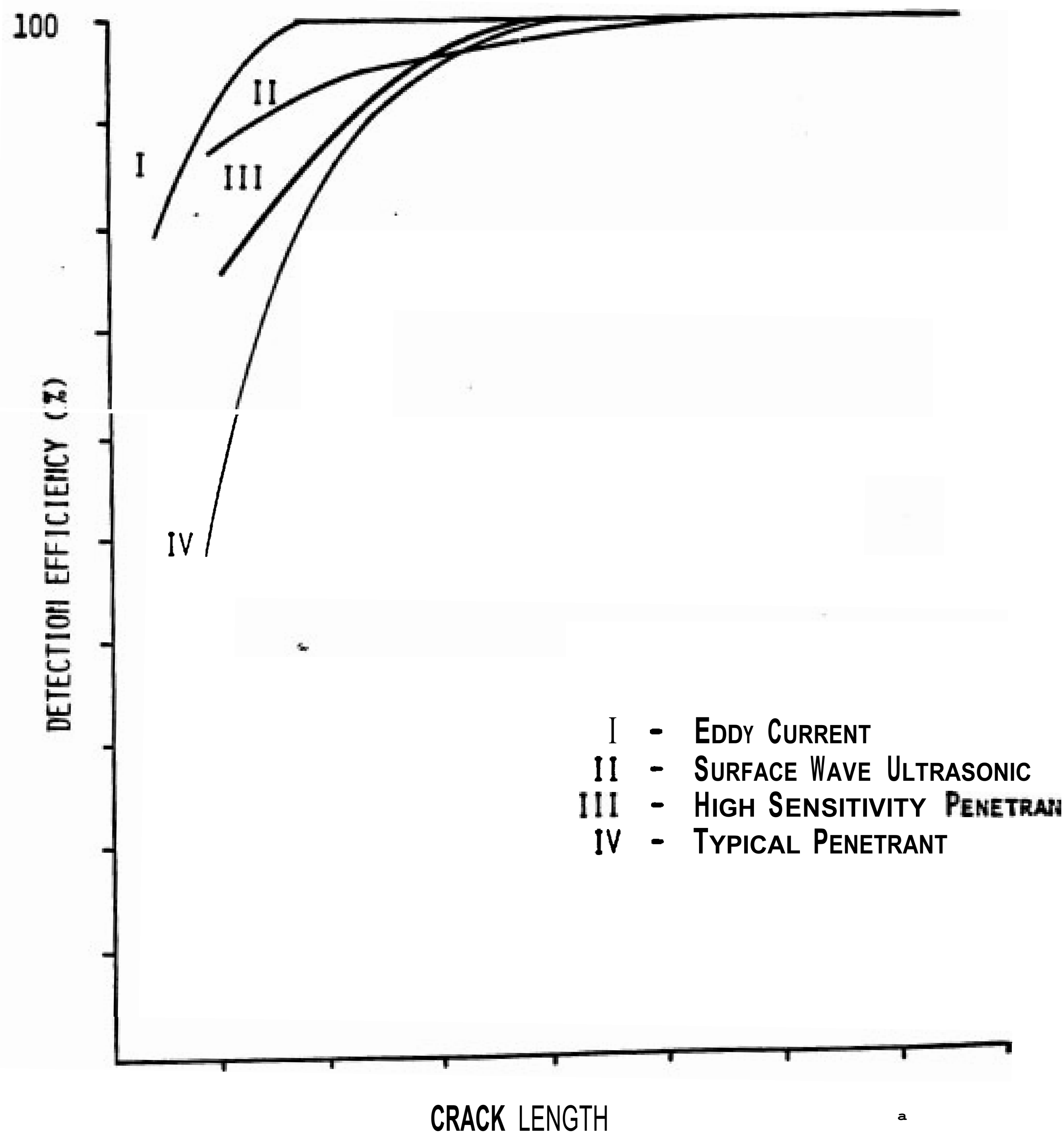


FIGURE 5.H.2

INSPECTION RELIABILITY (FOR)

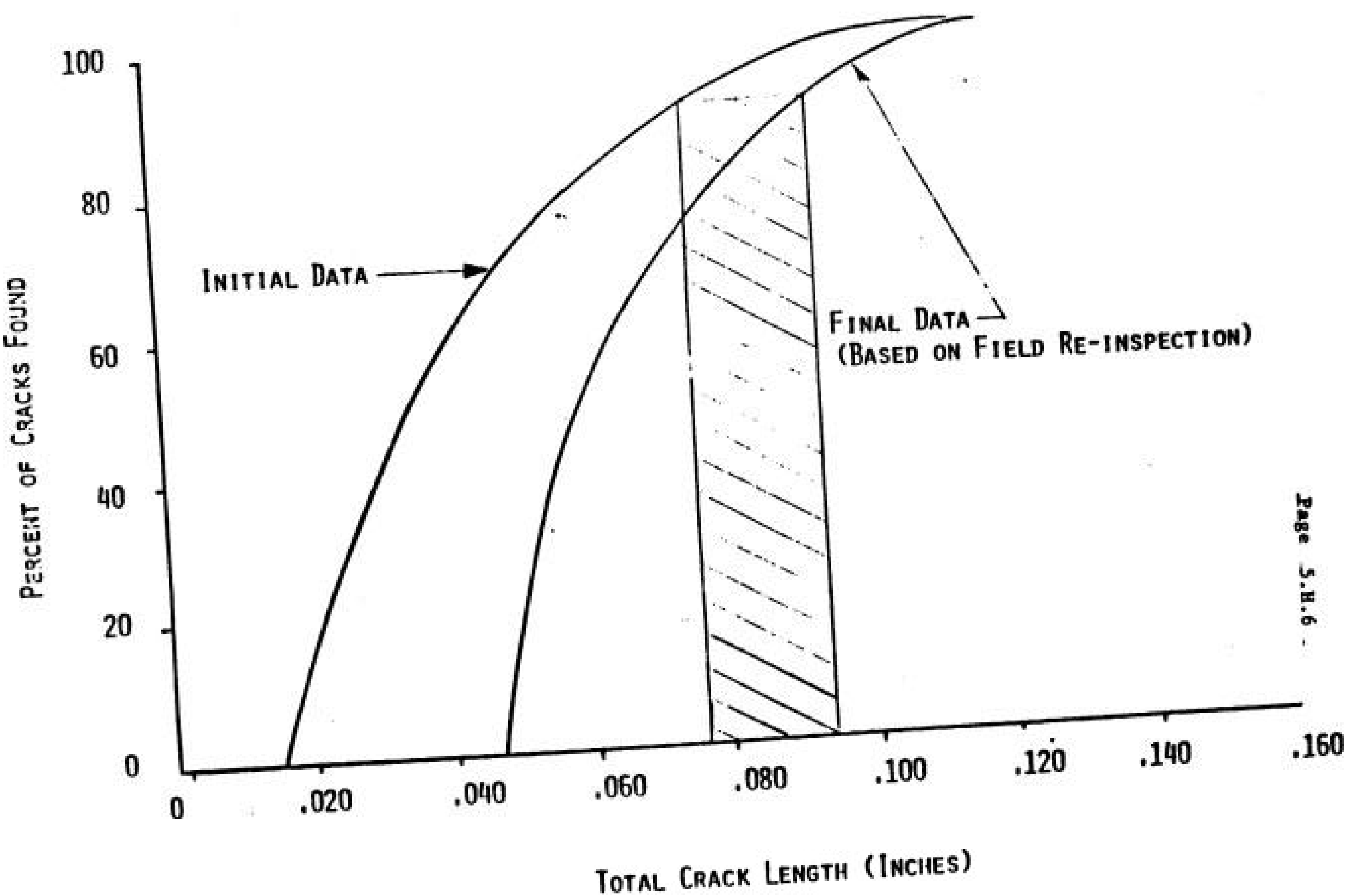


Figure 5.H.3

ULTRASONIC INSPECTION

Introduction:

This section on ultrasonic inspection will discuss the basic ultrasonic test (UT) fundamentals, significant process improvements, and the advantages and disadvantages of the ultrasonic inspection process. The Review Team has concentrated on the current practices of immersion UT presented in the following areas: personnel, standards and calibration, test requirements, and probability of detection.

Requirements for metallurgical analysis of confirmed defects, dispositioning suspect material as determined by UT and metallographic evaluation, and the retention of ultrasonic and metallographic examination records, will be discussed in the Engine Manufacturers' Quality Control Section (5.I) of this report.

Backaround:

Ultrasonic testing is a nondestructive inspection (NDI) method in which beams of high-frequency sound waves are introduced into materials for the detection of flaws. The sound waves travel through the material with some loss of energy (attenuation) and are reflected at interfaces. The reflected or transmitted beam is displayed and then analyzed to define the presence and location of flaws or discontinuities.

The degree of reflection is a function of the acoustic property mismatches (acoustic impedances) of the materials forming the interface. The acoustic impedance of a material is equal to the product of the density of, and the velocity of sound in, the material. Thus:

$$Z = \rho V$$

where Z = characteristic acoustic impedance
ρ = density of the material
V = velocity of sound through the material

and the degree of reflection, R, at the interface is:

$$R = \frac{(Z_1 - Z_2)^2}{(Z_1 + Z_2)^2}$$

where subscripts 1 & 2 refer to the two materials at the interface.

For example, sound waves are almost completely reflected at metal/gas interfaces, which makes cracks and voids readily detectable.

The principle advantages of UT for titanium parts and raw material stock are:

- Good penetration permits examination of thick sections.
- Good sensitivity permits the detection of small defects.
- Access to only one surface is required.
- Operation is electronic. This makes the method suitable for: instantaneous (i.e. real-time) indication of flaws: immediate interpretation; automation; rapid scanning; in-line production monitoring; and process control. Return signals may be processed digitally by a computer to characterize defects for determining with greater accuracy their size, orientation, shape, and nature. Lastly, a permanent record of inspection results can be made for future reference.

The disadvantages of UT include the following:

- Extensive technical knowledge is required for the development of inspection procedures.
- Interpretation of ultrasonic indications requires a high degree of training, experience, skill, and standards.
- Parts that are irregular in shape or of unfavorable geometries are difficult to inspect, and can produce defect-like indications.
- Defects must be oriented favorably to the sound beam for optimum detection.
- Discontinuities that are present in a shallow layer immediately beneath the surface may not be detectable, or may require extensive skill and knowledge to be detectable.
- Cracks and voids can be missed as a result of the high background-noise levels, and the high attenuation of ultrasound, in titanium.
- Large titanium segregation coincident with small voids or no voids is presently undetectable by ultrasonics.

Despite these limitations, UT remains the most viable method for detection of internal flaws.

Most ultrasonic inspection systems reviewed by the Titanium Review Team were pulse-echo systems, and included the following basic equipment:

- An electronic signal generator that produces bursts of voltage when electronically triggered.
- A transducer (probe or search unit) that emits a beam of ultrasonic waves when bursts of voltage are applied to it. Also, a transducer to accept and convert the return signal, from the testpiece, to an electronic signal. In most systems, a single transducer alternately acts as sender and receiver.
- A couplant to transfer energy from the transducer to the testpiece and from the testpiece to the transducer.
- An electronic device to amplify and, if necessary, demodulate or otherwise modify the signals from the transducer.
- A display or indicating device to characterize or record the output from the testpiece, i.e., oscilloscope and strip chart recorder or computer for storing digital signals.
- An electronic clock, or timer, to provide coordination for the entire system and serve as a primary reference point.
- Scanning equipment for automatically moving the testpiece and/or search unit.

Some of the improvements in the UT systems have been to these basic components:

- Transducer - Throughout the 1960's, 70's, and 80's, there have been continued improvements in quality, resolution, and noise reduction.
- Electronic instrumentation - Throughout the 1960's, 70's, and 80's, there have been continued improvements in linearity, noise reduction, electronic distance/amplitude compensation (DAC), and general uniformity.
- Couplant/scanning equipment - Immersion inspection was extensively implemented for titanium materials in the mid-1970's. This improvement allowed the inspection of sub-surface material without interference from

near-field effects. Other advantages include ocanning speed increase, ability to accurately position and direct sound beam, and adaptability for automated scanning.

- Scanning equipment - Computer controlled equipment permitted the contour-following inspection of complex geometries while achieving a high level of scanning coverage reliability.

<u>personnel</u>:

Some manufacturers do not have a standardized method or specification to evaluate and certify UT (or other NDI) inspectors. Currently, individual companies have their own test personnel requirements and recognize, as "certified", only their personnel. The Review Team believes that a national standard should be developed in order to identify minimum qualifications and required training and examinations, at all levels of expertise. The Team also recognizes that for the standard to be effective, industry-wide certification of NDI personnel is necessary.

<u>Standards and Calibration</u>:

In order to maintain the integrity of any UT examination, it is necessary to regularly verify the performance of the equipment. This standardization allows the same test procedure to be conducted at various times and locations, with reasonable assurance that consistent results will be obtained. In the titanium rotor manufacturing process, repeatability is attained by using test blocks (consisting of metal sections) containing artificial flaws (consisting of flat-bottomed holes). The bottom of the hole offers an optimum reflecting surface that provides a reproducible return signal. Test or reference blocks also provide a basis for estimating the sizes of any flaws that are found.

Numerous factors that affect the ultrasonic test can make exact quantitative determination of flaw size extremely difficult, if not impossible. One factor is the nature of the reflecting surface. (Reference Prior Rotor Failures Section (5.K).)

While a flat-bottomed hole offers an optimum and reproducible reflecting surface, natural flaws can be of diverse shape and offer nonuniform reflecting surfaces. The location and orientation of a flaw and the amount and type of forge working that the product has received will influence the shape of the flaw. For example, a pore in an ingot might be spherical and, therefore, scatter most of the sound away from the search unit, reflecting back only a small amount to produce a flaw echo. Flaws must be oriented favorably to an accessible scan surface. During forging, a pore usually becomes elongated and flat, and therefore reflects more sound back to the search unit.

Another factor to consider is ultrasonic attenuation in the titanium alloy. Rapid attenuation of ultrasound may result with large-grain microstructure (not refined due to too little working). In some cases, if grain size is quite large, it may not even by possible to obtain a back reflection at normal test frequencies. The extent of attenuation may determine whether a satisfactory ultrasonic inspection can be performed. Imparting too much work to the material, or improper thermal treatments, can also increase attenuation.

Additionally, the test block microstructure might not have attenuation characteristics similar to the material being evaluated. For example, if a reference block prepared from fine-grain steel were used to set the level of test sensitivity, and the material being inspected were coarse grained, flaws could be quite large before they would yield an indication equal to that obtained from a flat-bottomed hole in the reference block. For these reasons, the diameter of flat-bottomed hole in the reference block is not indicative of the size of the flaw in the testpiece (i.e. the part being evaluated).

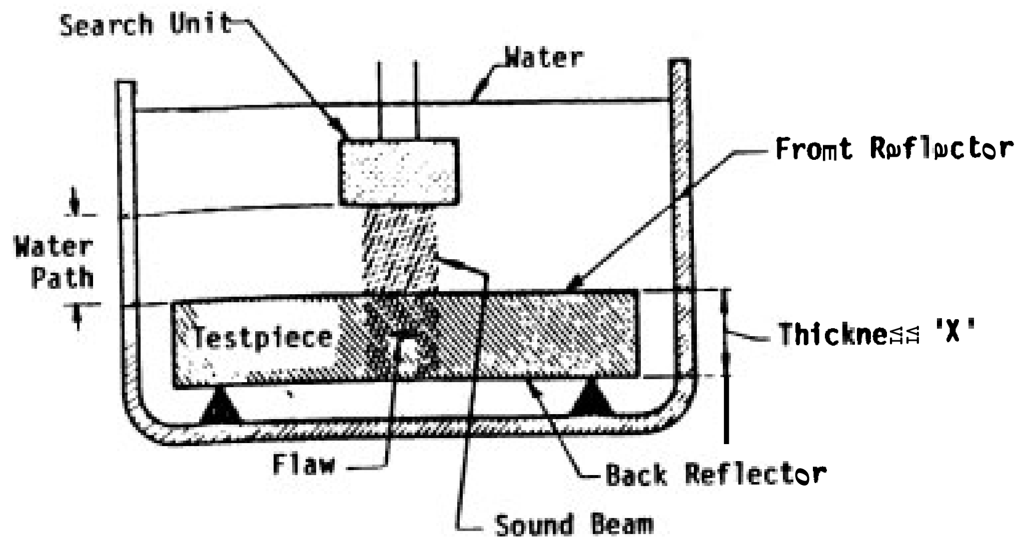
A potentially more accurate method would be to obtain test blocks containing natural flaws. Metal sections similar to those parts being inspected (and known to contain natural flaws) could then be selected as test blocks.

Test blocks containing natural flaws have only limited use as standards, for two principal reasons:

- It is difficult to obtain several test blocks that give identical responses. Natural flaws vary in shape, surface characteristics, and orientation; and echoes from natural flaws vary accordingly.

- It is often impossible to determine the exact nature of a natural flaw existing in the test block without destructive sectioning.

In summary, although test blocks are adequate to verify the proper operation of an ultrasonic test system, the Review Team is aware of no data which show that the ultrasonic signals, generated from test blocks, represent acceptable/rejectable sizes of Type I defects in actual engine parts.



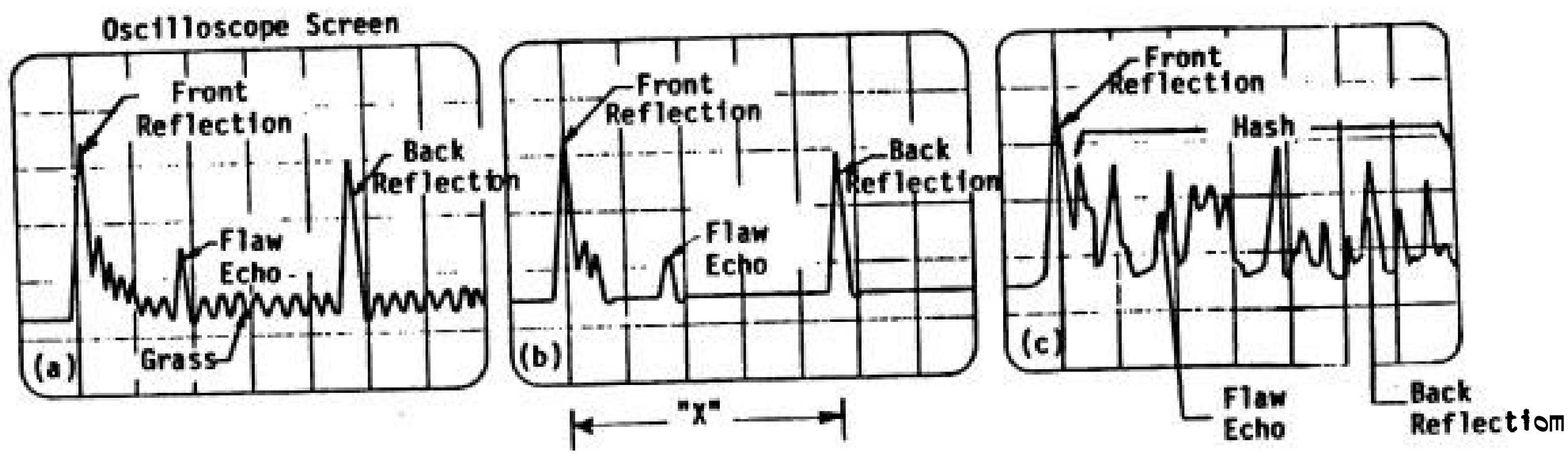


Figure 5.H.4 A-scan displays showing (a) appearance of electronic noise as grass; (b) grass filtered out by use of a reject circuit with some loss of echo-signal amplitude; (c) course grain indications (hash) that interfere with the detection of discontinuities.

Ultrasonic Test Requirements:

The oscilloscope screen in Figure 5.H.4, illustrates a typical video-mode A-scan display from a straight-beam test. The trace exhibits a large signal corresponding to the front-surface echo and a somewhat smaller signal corresponding to the back reflection. Between these two signals are indications of echoes from any interfaces within the testpiece; one small signal corresponding to the flaw shown in the testpiece appears between the initial pulse and the back reflection on the screen. Of particular concern are the spurious indications from reflections or indications of sources other than defects. Reflections from edges and corners, extra reflections due to mode conversion, and multiple reflections from a single interface often look like flaw indications. Sometimes, these false or nonrelevant indications can be interpreted as such, by correlation of the apparent flaw location with some physical feature of the testpiece. On other occasions, only the experience of the operator, and a thorough prior understanding of probable flaw types and locations, can separate nonrelevant indications from relevant indications of actual flaws.

There are certain other types of indications that may interfere with the interpretation of A-scan data. All electronic circuits generate a certain amount of noise coming from high-frequency harmonics of the main-signal frequency. Electronic noise generally is of low amplitude and is troublesome only when the main signal is also of low amplitude. In ultrasonic inspection, electronic noise can appear on an A-scan display as a low level, general-background signal, called "grass", which is shown in Figure 5.H.4. Many instruments are equipped with reject circuits that filter out grass, although usually with some loss of echo-signal amplitude. When reject circuits are used, they should be adjusted so that grass is reduced only enough not to be a hindrance. If too much rejection is used, small-amplitude echoes will be suppressed along with the grass, and there will be a loss in sensitivity of the inspection technique, and the linearity of the instrument will be affected.

A second type of interference occurs when coarse-grain materials are inspected. Reflections from the grain boundaries of coarse-grain materials can produce spurious indications throughout the test depth (see Figure 5.H.4). This type of interference, called "hash", is thus most often encountered in coarse-grain titanium, and as one would expect, is less troublesome in fine-grain titanium.

Engineering ultrasonic specifications use the general term "noise" to define signals on the CRT display caused by material structure, surface roughness, and/or electrical interference. Also, these engineering specifications require that inspection noise levels are no higher than approximately 80% of the minimum rejection limit specified. After discussion with several inspection sources, the Review Team believes that ultrasonic inspection specifications should reduce the allowable noise levels, especially the "hash", in premium quality titanium products. The lower noise levels would enhance flaw detectability (discussed later in this Section). This evaluation is of particular concern with large-diameter billet stock where attenuation in titanium is very influential.

Most companies visited by the Titanium Review Team were very concerned about ultrasonic interference due to titanium microstructure. One company is developing a procedure and equipment which uses digital signal analysis to improve flaw signal-to-noise ratio. Other companies are studying methods to further refine the alloys' microstructure in order to reduce noise.

The Review Team did not receive data showing: the allowable limits of attenuation levels for premium grade titanium, or the improvement in attenuation achieved by processing for more-refined grain structure. And specifications have not been standardized for evaluating forging attenuation properties. In addition, neither the engine manufacturers nor the titanium forging industry have developed a coordinated plan to reduce titanium attenuation. For these reasons, the Team was unable to evaluate the effect of attenuation on the quality of the forging product or on the quality of the inspection; and was unable to make specific recommendations as to the level of acceptability or the future capability of the forging/inspection process. Therefore, the Review Team believes that an industry-wide standardized material characterization test for attenuation should be developed, and performed on each billet, with particular emphasis on large-diameter billet. This test and its results should be recorded and monitored by the forging producer and engine manufacturer, in order to develop a better data base correlating NDI results with various material properties.

In conjunction with reduced specified noise levels during UT of premium grade titanium, we believe that the level of discontinuity acceptance limits could be more stringent, after reviewing the current production technology. All ultrasonic automated scanning equipment uses alarm gates in initial detection of unacceptable indications. During many inspections, the alarm gates are set too far above the noise levels. Alarm levels should be set just far enough above allowable noise levels to minimize false calls, while maintaining high discontinuity detection sensitivity. The goal for the degree of sensitivity should be representative of the maximum size flaw allowed by the design of that component. To date, the industry has not achieved

EDDY CURRENT INSPECTION

Eddy current inspection is used to interrogate surface and/or near-surface material for discontinuities in the form of defects or cracks. This method is dependent on the electrical conductivity of the material to be inspected. When electrically conductive material is exposed to an alternating magnetic field that is generated by a coil of wire (transducer) carrying an alternating current, eddy currents are induced on the material surface or in the near-surface material (see Figure 5.H.5). The effect of eddy currents, generating magnetic fields which interact with the magnetic field of the transducer to change its electrical impedance, can be measured. These measured changes in the impedance of the transducer can be used to detect surface or near-surface discontinuities which affect the current carrying properties of the test material.

Eddy current inspection has several advantages and disadvantages. The advantages of eddy current are that it: can detect both surface and subsurface discontinuities, can be used on ferrous and nonferrous materials, is more versatile than fluorescent penetrant inspection methods, has adjustable sensitivity, and is portable. The disadvantages in the use of eddy current are that: the applications are limited to electrically conductive materials, it requires reference standards and specific operator training, and there is difficulty in some cases in interpreting results.

Very little part preparation is needed for eddy current inspection. The surface of the area to be inspected may need to be cleaned or otherwise exposed so that the eddy current probe has adequate access. The inspection is accomplished real time, where the probe-sensed variations in impedance are displayed on a meter or cathode ray tube type of instrument. This allows the inspector to detect and re-inspect to confirm the presence of an indication prior to further interpretation.

Eddy current inspection has become a highly reliable method for detecting surface and near-surface defects, and has been utilized to enhance other surface inspection methods (e.g. visual and fluorescent penetrant) in validating the presence of defects, or for inspecting areas where visual observations are impracticable. In order to maintain high reliability in detecting defects, particular care must be taken in the setup of the eddy current system and in the interpretation of displayed signals. It is therefore necessary to ensure that the inspector is properly trained to operate an eddy current system.

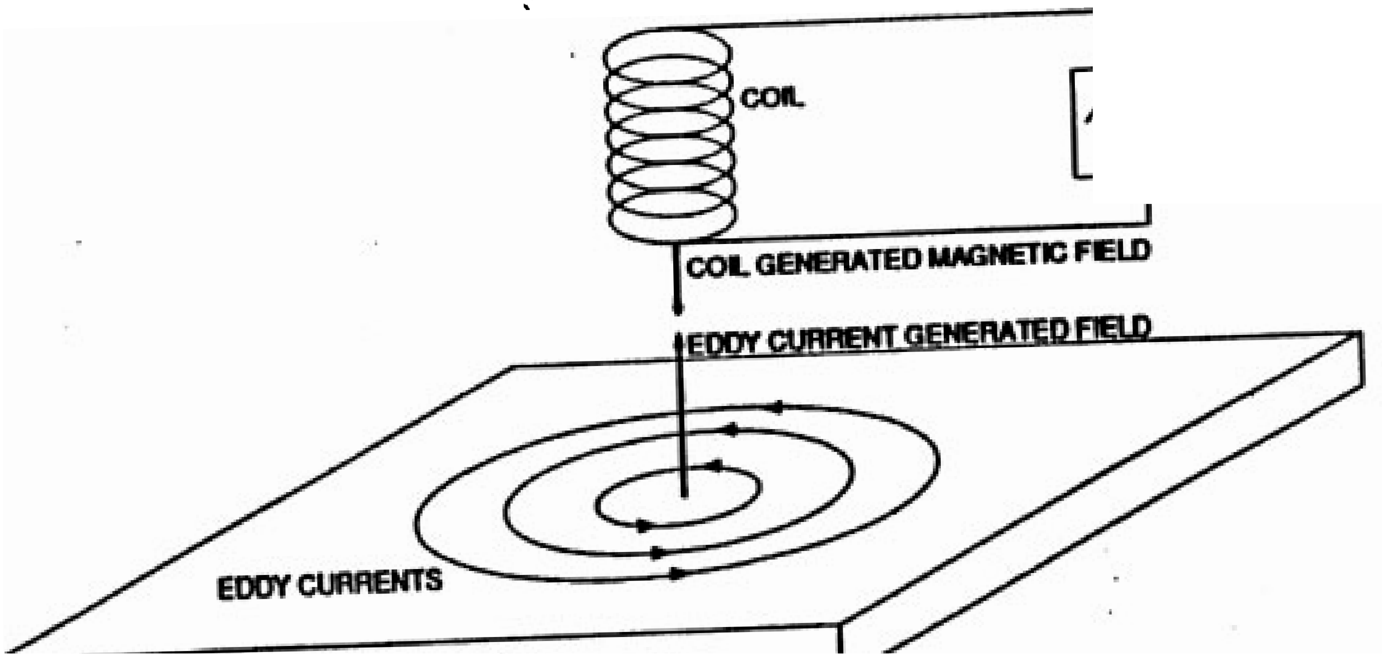


Figure 5.H.5
Induced Eddy Currents on Conductive Material

this desireable level of correlation between manufacturing and design.

Also, current ultrasonic indications are sized by direct comparison to a signal of a specified amplitude generated by a reference block. Because of the extreme difficulty in sizing indications accurately, as previously discussed, all discernable indications, which have been ultrasonically detected by the automated alarm/gating system, should be further evaluated. Methods that have been used to better evaluate an indication include adjusting probe frequency and focal length, and employing shear and longitudinal waves from all viable directions. Several inspection sources have reported that they are presently using these techniques, but not as standard requirements.

After this careful ultrasonic evaluation, if an indication is still suspect, metallurgical examination should be required regardless of signal amplitude. Some inspection sources have employed this procedure, but it is not required by specification. This analytical data could then be used to develop a relationship between real, subsurface flaws and smooth holes in a reference block.

UT System Reliability Assessment:

The UT system must provide qualitative information establishing the presence or absence of a flaw, and quantitatively measure the size of the indicated flaw. Ideally, the ability of an NDT system to attain this information should be assessed and should permit the quantitative comparison of one system with another with respect to known specimen standards. Reliability assessments have been performed by the Air Force using Proposed MIL-STD for USAF NDE System Reliability Assessment (dated August 31, 1989) developed under contract from WRDC/MLSA, Wright-Patterson Air Force Base, Ohio. These assessments, which require planning, conducting, analyzing, and reporting reliability evaluations, were defined in terms of the probability of detection (POD). The POD, for all defects of a given size and type, is postulated as the fraction (of the total number of those defects) that will be detected by an NDI system when applied by representative inspectors to a specific population of structural elements in a defined environment.

A truely accurate system reliability assessment for Type I and Type II defects is believed to be unachieveable for titanium rotor forging producers and engine manufacturers for the following reasons:

1. Subsurface, Type II defects are extremely difficult, if not impossible, to detect with current state of the art, NDI technology.

2. A Type I, or any other, internal defect specimen standard is difficult to manufacture accurately, and extremely difficult, if not impossible, to duplicate. Without accurate defect specimen standards, a precise and statistically proven ultrasonic system assessment is very difficult, and costly.

Nevertheless, the engine manufacturers, per FAR's (Federal Aviation Regulations) 21.143 and 33.15, are required to ensure that materials meet specifications and that inspection and test procedures insure that each rotor conforms to the type design and is in a condition for safe operation. Therefore, the engine manufacturers should define the limits of operational parameters and range of application, and demonstrate that this system is in control. In addition, statistical assessments of those factors responsible for system variability should be documented.

Some companies have initiated a UT system reliability assessment based on metallurgically sectioning and measuring the imperfection; however, at this time their findings appear inconclusive. Other companies are developing ultrasonic indication/flaw signal analysis whereby the size, shape, and orientation of the suspect flaw may be electronically determined. Some sources have suggested seeded heats containing natural flaws: but these programs are costly and have drawbacks as previously mentioned under "Standards and Calibration" above.

Some individuals believe that a detailed metallurgical evaluation of indications reported in billets, sonic shapes, and finished components, relative to ultrasonic signals generated by those anomalies, may be very effective. Confirmation and characterization of these imperfections in terms of size, shape, nature, and orientation would be reported along with the identification of the ultrasonic equipment, test technique, and signal output recordings. All testing and flaw characterization factors which affect the strength of a defect's signal should be reported. This task is slow and arduous; however, if all affected companies participate in an industry-wide effort, the accuracy and the completion time would be benefitted.

The highest likelihood of finding indications in finished components would be in rotors manufactured in the 1970's by the double vacuum melt process. The best source for finding indications in billet and sonic shapes would be in their respective shape examined with the low noise and smaller indication signal requirements.

INSPECTIONS IN SERVICE

The current turbine engine design philosophy uses the Safe Life concept (Page 5.5.4) for main rotor disks, but this does not necessarily mean that the disks can be safely operated to their (Safe Life) retirement age without being inspected from time to time. In-service disk inspections (e.g. the common engine practice of inspections-of-opportunity) are necessary to detect cracking caused by:

1) metallurgical defects undetected at manufacture (e.g. Type I, Type II, clean voids, etc.),

2) design errors (e.g. missed stresses &/or temperatures, etc.),

3) manufacturing errors (e.g. improper heat treatment, undersize fillet radii, etc.),

4) maintenance errors (e.g. faulty repairs, improper re-assembly, etc.),

5) operational errors (e.g. over-temps, over-speeds, etc.), and

6) any (other) accidental, mechanical or physical damage.

Inspections of opportunity, as the name implies, do not provide for positive nor uniform coverage of all disk serial units (serial numbers) in an engine fleet. Normally, a disk is inspected only when the engine (or module) is disassembled sufficiently to afford access to all surfaces of that disk. This means that there is always a distribution of inspection frequencies for a given disk part number: some serial units will have been inspected very often (say 7-10 times) during their service lifetime, most units will have been inspected several times (e.g. 3-6) during their service life, and some serial numbers will have been inspected only twice, once, or not at all during their service life. Therefore, inspections of opportunity, while occurring frequently enough for most disks (the Sioux City disk, e.g., had an opportunity for 6 inspections), result in a percentage of disks which receive only 1 or 2 inspections or no inspections during their service life.

Some airlines have an engine shop program which they develop through their reliability program, and which is a part of their continuing airworthiness maintenance program for the aircraft. This engine shop program is approved by the FAA's Principal Maintenance Inspector, and specifies disk inspections at certain intervals, e.g., 5, 10, 15, and 20 thousand flight cycles.

However:

1) these are "soft-time" as opposed to "hard-time" inspections, meaning that the cyclic intervals are only approximate values (which may be exceeded), and the specified intervals do not require the engine to be removed from service if this would be the only reason for so doing,

2) many operators do not have an engine shop program, and

3) intervals for disk inspection are not usually specified by the engine manufacturers in their respective maintenance manuals.

Therefore, because of:

a) the frequency of occurrence of titanium metallurgical defects,

b) the difficulty of detecting defects in titanium (especially void-free and crack-free defects),

c) the many sources of defects, errors, and damage, as listed above,

d) recent developments in the engineering science of fracture mechanics (crack propagation) analysis, and

e) the development of Monte Carlo reliability simulation/ analysis as applied to engineering problems,

the Review Team believes that the random approach of inspections of opportunity is not adequate, and can no longer be justified.

For the first time, a scientific approach to the determination of a safe inspection frequency for commercial engine disks is believed practicable through application of the above mentioned newly improved engineering sciences. But implementation of this approach will be a major task for the industry as well as the FAA, and may take 2-3 years, or more. Therefore, until the engine manufacturers have time to: develop the necessary engineering data (e.g. in-service POD curves, flaw size distributions, etc.), complete the analyses, develop and manufacture the necessary inspection tooling, and coordinate implementation plans with the aircraft owners/operators, an interim plan should be implemented (within 6-12 months).

The proposed interim plan is less scientific than a fracture mechanics technology approach, but more positive (less random) and more defect-sensitive than the current inspections-of-opportunity approach. The near-term interim plan consists of supplementing the current inspections of opportunity (which are full-disk FPI's) with ECI of the highest stressed locations (e.g. bore and bolt circle, but not necessarily the blade slots at the rim) on each disk. The FPI and the ECI should be done at the same time, and at the frequency currently used for FPI.

The longer-term interim plan consists of adding a subsurface inspection (e.g. ultrasonic) to the above, enhanced surface inspection (i.e. to the near-term plan). The subsurface inspection should be performed at least twice during each component's certificated cyclic life, at intervals acceptable to the Administrator.

An example of an acceptable interval for the subsurface inspection would be: 1/3 ± 1/6 and 2/3 ± 1/6 of the part's certificated cyclic life. Every disk serial unit would have at least 2 inspections of this type during its operational lifetime, and these 2 inspections should be spaced no closer than 1/6 of the disk's certified cyclic life.

The inspection windows (i.e. ± 1/6 or 2/6 or 1/3 of the certified cyclic life for each inspection) are large enough so that, in the vast majority of cases, engine removals outside the current maintenance removal frequency will not be required, and module disassemblies (just for the new "soft hard-time" disk inspection) will not be necessaty. Any other naturally arising inspections of opportunity will only require the full FPI and localized ECI (of the near-term interim plan) described above.

The advantages, of inspecting at approximately 1/3 and 2/3 of the disks's certificated cyclic life, are that the disk is looked at early in its operational life in order to discover any gross error, defect, or damage that could result in infant mortality (early rupture): and the disk is looked at fairly late in its operational life when the probability of cracking has substantially increased. (The probability of fatigue cracking increases throughout a disk's cyclic life.) The 2/3-life inspection, of course, (like the 1/3) will also discover problems resulting from errors, defects, and damage.

Figure 5.H.6 further illustrates/explains this concept.

RATIONALE FOR 2 INSPECTIONS

```
 |------------------------|------------|-------------|-----------------------|
0% PSCL                 33.3%        50%          66.7%                 100% PSCL

                        1/3                        2/3
```

PSCL = Predicted Safe Cyclic Life

1. A Design Factor of Safety (F.S.) of 3 has been shown to be optimally conservative in roughly 100 years of service experience with structures and machines of all kinds. A F.S. of 3 is not scientifically based, but is based on long (vast) practical experience.

2. One inspection, at approx. 50% PSCL, would be too late to protect against infant mortality problems, and may be too early to detect late blooming problems.

3. 1/3 and 2/3 PSCL not only provides a F.S. of 3, but addresses cracking near both ends of the life spectrum, and in the middle.

4. Comprehensive Engineering Life Reviews (service sampling) at 1/3 and 2/3 PSCL:

   : Adopted by BCAR's (British Civil Airworthiness Requirements)

   : Adopted by JAR's (European Joint Aviation Requirements).

CONCLUSION: 2 inspections, approximately equally spaced over the PSCL, are optimum until scientifically-based, Fracture Mechanics intervals are established.

Table 5.H.1 is a ranking of the 24 titanium disks which failed in commercial service, due to metallurgical defects, prior to the Sioux City disk. Careful study of these data reveals the following:

Observations:

1. Fifteen of those 25 disks (including the Sioux City disk) actually burst.

2. With only 1 hard-time inspection at 1/2 of the approved cyclic life (ACL) and with the current I of O (inspections of opportunity), 15 of the 25 disks would still have burst.

   (This, and Observation number 3, are based on these assumptions: If the cracks (in Table 5.H.1) preceed the hard-time inspection by 1/6 ACL or more, the hard-time inspection would be too late to prevent burst. And if the cracks or bursts (in Table 5.H.1) follow the hard-time inspection by 1/6 ACL or more, the hard-time inspection would be too early to detect a problem.)

3. With 2 hard-time inspections at 1/3 and 2/3 of the approved cyclic life (ACL) and with the current I of O, 10 of the 25 disks would have burst.

Conclusions:

1. Two soft hard-tihe inspections (i.e. at 1/3 ± 1/6 and 2/3 ± 1/6 ACL) are what is recommended for the longer term interim solution (18- to 24-month incorporation time).

2. This is obviously still inadequate as a permanent solution since 10 of the 25 disks would still have burst. Thus the need for a fracture-mechanics based inspection interval as recommended in the "final" resolution column (2- to 3-year incorporation time) of Table 5.H.2.

Therefore, until the more scientific fracture-mechanics approach is implemented, a program consisting of the current inspections of opportunity (FPI's) strengthened by ECI and UT at the above stated intervals, is the optimum that can be achieved. These inspections are summarized in Table 5.H.2.

TABLE 5.H.1

TITANIUM DISKS WHICH BURST OR CRACKED, DUE TO METALLURGICAL DEFECTS* IN SERVICE, PRIOR TO SIOUX CITY DISK

	Percent, of approved cyclic life at which failure was discovered:		
1.	2.1	B	(B = burst)
2.	2.9	C	(C = cracked)
3.	9.3	B	
4.	10.9	B	
5.	12.3	B	
6.	13.0	B	
7.	13.4	B	
8.	21.0	B	
9.	31.9	B	
10.	32.0	B	
11.	33.9	C	
12.	34.0	B	
13.	38.2	B	
14.	42.3	C	
15.	48.2	C	
16.	48.9	C	
17.	49.4	B	
18.	61.9	C	
19.	64.9	C	
20.	71.0	B	
21.	72.3	C	
22.	79.2	C	
23.	80.3	B	
24.	86.1	B	(Sioux City disk)
25.	88.4	C	

41.9 = Mean percent life at discovery.

38.2 = Median percent life at discovery.

* These metallurgical defects include: Types I & II, other segregation types, voids, and porosity.

ENGINE MANUFACTURERS' QUALITY CONTROL

The engine manufacturers' Quality Control Plans for the acquisition of premium grade titanium based alloys are sourced in the particular manufacturer's material and process specifications. The various engine manufacturers identify sources for materials and processes, and qualify them in accordance with established procedures. Then through the medium of vendor agreements, they freeze the process controls. From that point on, purchase order clauses govern the material quality control requirements based on technical data acceptance characteristics and the existing process controls agreed upon.

A change in process control requires review and approval by the engine manufacturer in accordance with the vendor agreement. The submittal of a nonconforming characteristic by the vendor requires a material review disposition by the engine manufacturer. Changes in process or product requested by the engine manufacturer, obviously require negotiation with the vendor, in addition to submitting a purchase order amendment to identify changed requirements.

Quality requirements include material specifications, processing parameters, material and process sources, inspection techniques, and control of inspection acceptance media. Records of material and process traceability, chemical and physical characteristic verification, and inspection acceptance are of paramount importance.

The selection, qualification, and approval of sources of titanium material, processes, and parts are performed by an FAA-production-certificated manufacturer through a coordinated effort of the manufacturer's purchasing, engineering, and quality organizations. The vendor's facility, process capability, and process controls are evaluated for compliance with the engine manufacturer's design, material, and process specifications, and quality control system requirements. A vendor agreement is drawn up to control process procedures and manufacturing routines.

The engine manufacturer's vendor quality organization performs a vendor approval survey for production startup. The qualified vendor is then placed on a cyclical audit program. Audit frequencies are impacted by events and industry dynamics, i.e., vendor ratings, manufacturing and inservice difficulties, process refinement, and changing applied technology.

Sub-tier suppliers of revert chips, master alloys, NDI processing, etc., are similarly qualified and approved. These vendors are identified in the certificated manufacturer's approved supplier listing, and are authorized to be used by that manufacturer's supplier family.

TABLE 5.H.2

IN-SERVICE INSPECTIONS

EXISTING DISKS			
CURRENT MAINT. MANUAL REQMTS.	NEAR-TERM INTERIM RECOMMENDATION (6-12 MONTHS)	LONGER-TERM INTERIM RECOMMENDATION (18-24 MONTHS)	FINAL RECOMMENDATION (2-3 YEARS)
I of O (Inspections of Opportunity)	Supplemented I of O	Supplemented I of O; and Soft Hard-Time Subsurface Inspection	Fracture-Mechanics -Based Inspection Intervals
Full FPI every opportunity up to retirement life	Full FPI & local ECI, every opportunity up to retirement life	Full FPI & local ECI, every opportunity up to retirement life: AND Subsurface inspection (e.g. UT) at least twice during operational life, at FAA-approved cyclic intervals	UT &/or ECI &/or FPI, every X cycles up to retirement life; minimum of 2 inspections at FAA-approved cyclic intervals

NEW-DESIGN DISKS
(POSSIBLE FUTURE DIRECTION, EXAMPLE ONLY)
Design requirement: 10^{-9} per engine flight cycle, joint-probability of burst due to metallurgical defects
FM (fracture mechanics) -based inspection intervals
UT &/or ECI &/or FPI, every X cycles up to retirement life. (If inspections are done only twice, which is the minimum allowable, they must be done at 1/3 ± 1/6 and 2/3 ± 1/6 of the disk's cyclic life, and may not be closer than 1/6 of the cyclic life.)

ENGINE MANUFACTURERS' LIFING METHODS

Turbine Engine Fatigue Life Determination

INTRODUCTION

The design criteria for critical rotating engine components includes establishing a life beyond which the failure probability increases too rapidly. This increasing failure probability is caused by structural damage induced by cyclic stresses as a result of centrifugal forces due to rotation at high speeds, vibratory stresses due to imbalance and aero loads, and thermal stresses due to temperature gradients. The damage created by these in-service stresses is cumulative and is known as fatigue damage.

The word fatigue was first used to describe aging due to cyclic loading by the French engineer, Poncelet in 1839. The first known research into the fatigue phenomenon, however, was conducted by August Wohler, Director of Imperial Railways in Germany between 1847 and 1889. Wohler's research was related to railroad car axle failures occurring from repeated reversed-stress. During the last century the word fatigue has been accepted to refer to the degradation of materials in response to cyclic stresses or strains (repetitive loading & unloading).

DISCUSSION

The degradation of materials (fatigue damage) due to cyclic stress or strain is a function of the peak and range, of stress or strain. The peak and range, of stress or strain, can be expressed in terms of the maximum stress, and stress ratio, R. The stress ratio, R, is defined as the minimum stress divided by the maximum stress for any one cycle, The fatigue life of a component decreases: with increasing peak stress, and with decreasing stress ratio, R.

Since stress peaks and ratios may vary during cyclic loading of structures, it became necessary to develop methods whereby fatigue lives could be predicted as a function of these varying loads. The most widely used method thus far developed is the Palmgren-Minor Rule [1,2] (linear damage summation), which was proposed for predicting crack initiation life from empirical data.

The Palmgren-Minor Rule predicts fatigue failure when the sum of the ratio of applied cycles to allowable cycles equals 1.0. The allowable cycles, as a function of stress level and R ratio, are established by element testing for each material type, geometric stress concentration factor, and temperature.

In general, fatigue life determination over the years has been divided into two types. One type of cyclic loading behavior is where significant plastic strain occurs during each cycle. This type of behavior is characterized by high stresses and short lives (i.e. low numbers of cycles to result in fatigue failure) and is therefore referred to as low cycle fatigue (LCF).

The other type of cyclic loading behavior is that where the strain cycles are predominantly confined to the elastic range. This type of behavior is characterized by lower stresses and longer lives (i.e. high numbers of cycles to result in fatigue failure) and is referred to as high cycle fatigue (HCF), and high frequency fatigue (HFF).

Low cycle fatigue (LCF) is generally considered to be in the range of 100 cycles to 100,000 cycles, and high cycle fatigue (HCF or HFF), in the range above 100,000 cycles.

Several key points concerning fatigue are raised from the above definitions:

1) Fatigue is a <u>progressive</u> process. While a fatigue failure may occur suddenly, with no apparent warning, the mechanical process involved has been operating since the initial usage of the part.

2) The fatigue process is sensitive to local effects in a part such that fatigue damage may be concentrated to certain areas rather than throughout the structure. Some examples of local effects are: changes in geometry, thermal gradients, residual stresses, and material discontinuities.

3) The fatigue process culminates in cracks, or complete fracture (i.e. rupture or burst).

Although there is no universal agreement on the microscopic details of crack initiation and propagation, it is agreed that fatigue failures are caused by a crack that propagates to a length such that the remaining material can no longer withstand the local stresses and strains, and rupture occurs.

4) In the past, the overall failure process has been viewed as taking place in two phases:

   a) a crack nucleation and initiation phase, and

   b) a crack propagation phase.

These two phases of the fatigue failure process have been analytically evaluated by two distinct and different methodologies. The nucleation and initiation phase has generally been evaluated by the linear cumulative damage concept of Palmgren and Minor described earlier. The crack propagation phase has been evaluated using linear elastic fracture mechanics methods.

This division of analytical methodologies, to describe the overall fatigue failure process, has created considerable confusion in the past. The confusion has arisen in defining the term "initiation" in the first phase. The second phase of the failure process depends upon a knowledge of the crack size at the beginning of the propagation phase, but this crack size is not predicted by the Palmgren-Minor analysis, and therefore the end of the initiation phase is not defined.

The division of these two analytical methodologies depends, to a large extent, on the background of the reviewer. A physicist, interested in the atomic structure of the materials, would think of fatigue as all propagation. This is also true of a fracture mechanics specialist. A metallurgist may think in terms of a micro crack on the order of the size of a crystal grain visible by a scanning electron microscope (SEM). An engine design engineer may think in terms of cracks that are detectable by some non-destructive inspection method. As can be seen, the term "initiation" is arbitrary depending on the viewpoint of the reviewer.

Over the last decade, advances in electron microscope fractography have made it possible to determine that the overall failure process is propagation. It has been possible to trace fatigue striations down to the boundaries of inclusions and tool marks, to nearly the first loading cycle. This fact, coupled with modern fracture technology, has enabled a single analytical methodology to be established which can replace the dual methodologies, thus providing a means to predict residual strength as a function of time (cycles), not possible with the Palmgren-Minor approach.

Fatigue Method Definitions

Over the years, four basic fatigue method definitions (concepts) have emerged for aircraft turbine engine design:

1) Infinite-Life Method

This method implies unlimited safety with respect to fatigue. As mentioned previously, August Wohler conducted the first directed research into the fatigue phenomenon and introduced the concept of the stress-life (S-N) curve. This curve, established by element and component testing, depicts increasing life with decreasing stress. The curve becomes asymptotic at the Endurance Limit of the material, generally in the region beyond 1,000,000 loading cycles. The Endurance Limit is the value of stress below which the component life can be expected to be infinite.

2) Safe-Life Method

This method implies that parts are designed for a finite service life during which no significant damage, resulting in detectable cracks, occurs. The method assumes that the part contains no defects, and in-service inspections are not required to meet minimum life requirements (again, assuming no defects, errors, or damage). Upon reaching the life limit, the individual part is retired from service.

The safe life method is essentially a correlative procedure. A large data base of specimen, component, and complete-assembly testing is used to establish stress/strain life plots for selected temperatures and stress concentration factors. These are input into a fatigue algorithm, illustrated by Figure 5.J.1, to determine part life.

Non-destructive inspection is used during the initial manufacture of the part as a limiting device to ensure that parts entering service do not contain potentially hazardous defects. It is also used to remove those parts that develop cracks in service (on an inspections-of-opportunity basis).

Efforts may not always be made in the design/development phase to consider NDI requirements and limitations as part of the structural analysis. However, once design engineering is completed (if not before), quality methods and standards are established to ensure that defective parts do not enter service.

3) Effective (or Equivalent) -Initial-Crack-Size Method

As mentioned earlier, the overall fatigue failure process has been viewed as divided into two distinct phases: crack initiation and crack propagation. It was also mentioned that advances in fracture technology in recent years have allowed the overall failure process to be evaluated by a <u>single</u> (fracture mechanics) analytical approach. In this case, a safe life is established based on the crack growth life starting with a determined, effective initial crack size, and ending with a fraction of the critical crack size for some overload condition, e.g. overspeed.

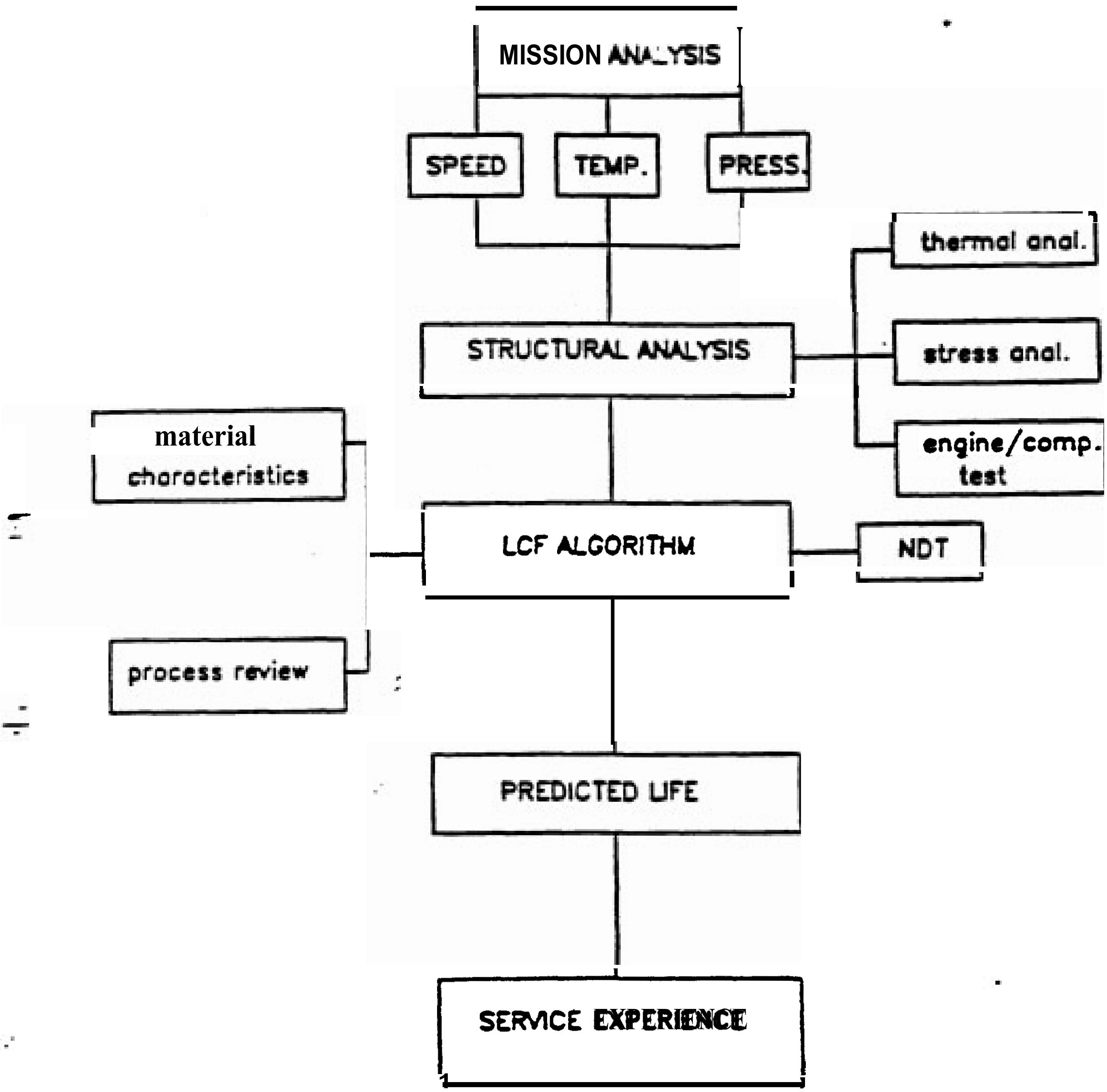

MISSION ANALYSIS
SPEED
TEMP.
PRESS.
thermal anal.
STRUCTURAL ANALYSIS
stress anal.
engine/comp. test
material characteristics
LCF ALGORITHM
NDT
process review
PREDICTED LIFE
SERVICE EXPERIENCE

FIGURE 5.J.1

The cumulative probability of effective initial crack sizes is statistically established to represent the initial manufacturing quality of the component, by fractographically back-tracking striations on the fracture faces of a substantial amount of test and in-service components. Based on this data, an initial crack size is selected such that the probability that its size will be larger, is extremely low. The initial crack size thus determined is called the "effective" initial crack size, and is a function of material type and manufacturing method.

One of the main advantages of this fracture mechanics approach to establishing a safe life, is that residual strength as a function of time (cycles) can be established. This is not possible with a linear cumulative damage approach. The effective initial crack size method has also been proposed to determine economic life for airframe components as described in reference [3].

4) Damage-Tolerance Method

Damage Tolerance is defined as the ability of a part to resist failure due to the presence of flaws, cracks, or other damage, for a specified period of unrepaired usage.

As shown in Figure 5.J.2, Damage Tolerant Design depends on three equally important, independent factors:

a. crack growth evaluation,

b. residual strength evaluation, and

c. inspection.

Two philosophies have emerged in damage tolerant design:

a. Crack growth life is determined using fracture mechanics technology, starting with a maximum defect size which may remain undetected during manufacture of the part. The NDI methodology used during manufacture is usually more sophisticated than exists in the field. Stress levels are established so that crack growth life, starting with the initial detectable crack size, is at least two design life-times. In-service inspections may not be necessary: however, sometimes they may be, in order to protect against the many sources of defects, errors, and damage listed on Page 5.H.19.

b. The overall fatigue life of the part may be established using the safe-life concept: but safety in the presence of defects, errors, and damage, which may exist

ELEMENTS OF DAMAGE TOLERANT DESIGN

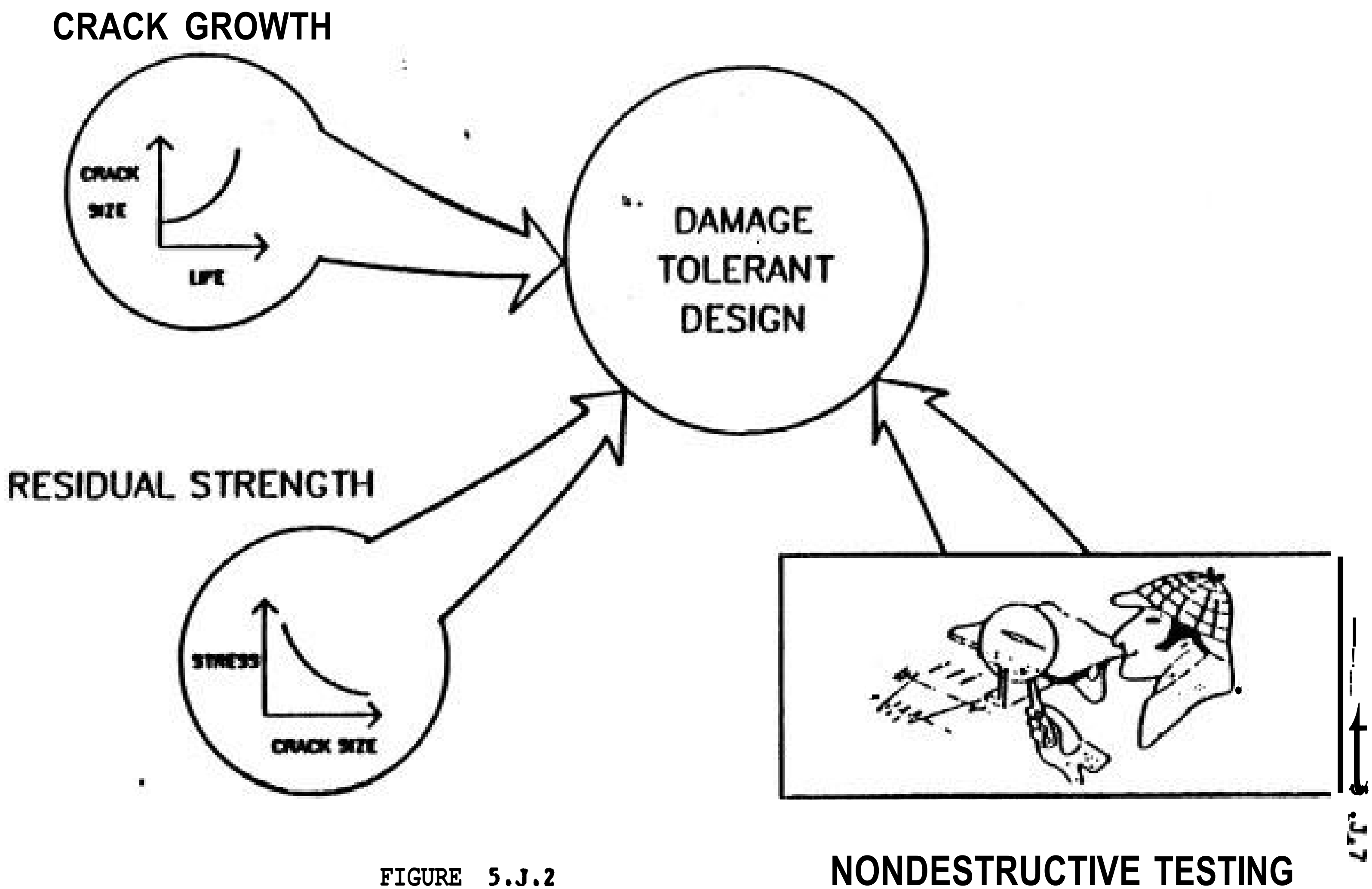


FIGURE 5.J.2

initially or may develop in service, is assured by in-service inspections. The in-service inspections may be less sophisticated than inspections used during initial manufacture. This method, often enforced by Airworthiness Directive (AD), is used to maintain safety at locations known to have developed abnormalities in service, until these locations can be redesigned and modified.

Two conclusions may be drawn from a damage tolerance evaluation:

a. The larger the initial flaw size, the shorter the total life. If the critical crack size (unstable crack growth) is equal to or smaller than the crack detection capability, failure may occur prior to damage detection. This situation, then, would suggest that "safe life" is the more appropriate lifing methodology to apply. Only when the critical crack size is significantly larger than the "first crack" detection size, can it be stated that the design is damage tolerant.

b. The definition of failure (e.g. burst: crack growth to some established limit: initial detectable crack size based on a specific NDI technique: or crack initiation) affects total life. Therefore, each design must be evaluated to define what constitutes failure.

These observations are crucial to a damage tolerant design. Once the end points (i.e. initial flaw size, in-service detectable crack size, critical crack size, and/or design (desired) life) are defined, the fracture mechanics analysis can determine the maximum allowable (local) bulk stress for the design.

Turbine Engine Design

The early concepts used for gas turbines were derived, principally, from experience gained on reciprocating engine superchargers and turbo-superchargers made from aluminum alloy and ferrite steels. Mechanical integrity of rotating parts was based on rotor overspeed being the limiting stress factor. Durability problems in the hot section (burner cans and turbine blades) resulted in short lives of hot section parts.

Consequently, there were frequent engine tear-downs for hot section inspections and overhauls, at which time any cracked parts were rejected. The low loading (due to temperature and speed), the relatively good material capabilities, and the low times (number of cycles), resulted in infrequent cracking occurrence.

As the demands on design engineers grew, materials with higher yield strengths, higher creep strengths, and lower densities, were needed, leading to the introduction of nickel-based super alloys and titanium alloys. Up until this time, in the mid to late 1950's, fatigue had been considered a phenomenon associated with vibration and resonance, something to be designed around, using the infinite-life method described earlier.

Then (in the mid to late 1950's), with the higher operating stress levels allowed by the tensile properties of the new materials, the longer time-between-overhauls created by better hot section materials, and the differing behavior of new alloy systems, it was found that the old design/development concepts were not sufficient. A number of test engine and service failures occurred at unacceptably low lives.

Analysis of the failures soon showed that, at the stress levels permitted by the overspeed design criterion, fatigue failures could occur in a small number of cycles related to numbers of aircraft flights or missions. This phenomenon was soon reproduced in simple laboratory tests and, by the early 1960's, empirical data banks were established of stress/life (S/N) plots covering various temperatures and component features (i.e. "notches").

This approach was added to the early component behavior concept as setting an additional stress limitation during the design phase. The maximum permitted stress was set by the required life, or vice versa, and read off fatigue design curves. These fatigue design curves were: derived from laboratory measured data, modified by component test results, and treated with suitable factors to allow for variability in material properties.

The approach eventually developed into the safe-life method for aircraft gas turbine, critical rotating components. Because of the inherent scatter in fatigue lives, due primarily to material variability and surface-finishing techniques, it became necessary to represent the data statistically. A number of reliability methods have been used, including the use of the Log Nonnal and Weibull probability distributions.

A minimum standard for LCF (safe) life, historically accepted by the Federal Aviation Administration (FAA), has been defined as the number of cycles at which, statistically, one out of a thousand parts, at retirement, will have developed a crack (or cracks) having surface length of 1/32 inch. Although this standard of life to "initiation" is somewhat arbitrary, the following three factors are responsible for its development:

1. A 1/32 inch crack was the smallest length that could be reliably detected by then current fluorescent penetrant inspection methods.

2. For then current rotor materials, a 1/32 inch long crack was significantly smaller than critical length.

3. A crack of 1/32 inch length would not propagate under high-frequency vibratory stresses typical of most, then current, rotor components.

With only a couple of (noteable) exceptions, all manufacturers of commercial aircraft turbine engines are using a safe life philosophy based solely on a linear cumulative damage approach, to establish safe operating lives for their critical rotating components. These safe lives are specified at the time of certification, or incrementally as service experience is gained. However, in a number of special isolated cases, the 1/32 inch standard for a safe-life limiting crack size, has been extended when supported by substantial in-service data.

In these cases, a safe life limit has been established which includes both crack initiation and crack propagation, beyond the 1/32 inch long crack. The materials, design details, temperatures, and stress gradients in these cases are such that the propagation life is a substantial portion of the overall life to a critical crack size at overspeed stress levels.

As fracture mechanics technology has advanced, it has become possible to establish sufficient data to reliably incorporate the effective-initial-crack-size method, described earlier, to establish safe lives for critical rotating components manufactured in certain materials. This philosophy, used by one engine manufacturer, has gained FAA approval.

To date, none of the lifing methods, used for the design of commercial turbine engine critical rotating parts, have accounted in a deterministic way, for initial defects which remain undetected. That is to say, safe lives are not established, based on crack growth starting with an initial defect size that is inspectable at manufacture, using a deterministic crack growth evaluation procedure.

However, one engine manufacturer's safe-life method has, for some time, included a statistical procedure which accounts for the distribution of expected initial defects using a joint-probability (Monte Carlo reliability simulation/analysis) procedure which accounts for variations in initial flaw size, probability of flaw detection, flaw orientation, material variabilities, etcetera. This procedure is taken into account when establishing design stress levels at that company.

U.S. Air Force Engine Structural Integrity Program (WSIP)

The U.S. Air Force has discontinued the use of the "safe life" philosophy for both airframe and engine structural design. In the case of engines, within the ENSIP, the Air Force has adopted a damage tolerance philosophy for design. Two approaches are being used, based on:

a. Non-Destructive Inspection (NDI), and

b. Proof-Load Testing.

NDI Approach

In the case of NDI, the introduction of damage tolerance to engine disks has required the development of centralized, sophisticated, computerized, inspection technology to find defects small enough to make a damage tolerance philosophy feasible. The system is based on high frequency eddy current inspection (ECI). Equipment to perform inspections capable of detecting surface defects with depth as small as 0.005 inch and surface length as small as 0.010 inch, with 90% reliability and 95% confidence, is in place within the Air Force and also within many of the engine manufacturers.

The philosophy includes: performing the inspections to ensure the finding of defects larger than 0.005 inch deep, and establishing a residual strength capability for an overspeed condition. The resulting life is divided by two (2), and the disk is put into service for this factored life.

Proof-Load Testing Approach

Certain disks, made from materials which require screening for smaller flaws than can be reliably found by NDI, are loaded beyond their residual strength for a given flaw size. If the disk survives this proof load, it is proven that no flaws beyond a given size are present, and the disk is placed in service for a specified life.

This philosophy has been used for pressure vessels, and F-111 and B-52 airplane wings. In the case of engine disks, spin pits operating at cryogenic temperatures are used to screen defects. The disks are spun to an overspeed condition after temperature reduction to cryogenic levels. If the disk remains intact throughout the test, it is known that flaws equal to or greater than that which would be critical at the service-operational stresses and temperatures, do not exist in the disk.

This flaw size, determined analytically by fracture mechanics, is used as the starting flaw for a crack growth analysis performed at the operating stress levels and temperatures. The resulting crack growth life is divided by two (2) to provide a life to which the disk can be safely operated. After this life has been used, the disk may be returned to the spin pit where the same procedure could again be applied.

Cryogenic temperatures are used because the materials to which this test is applied, have significantly lower fracture toughness at these temperatures than at the service operating temperatures or at room temperature. Thus a smaller flaw can be screened, allowing a longer crack growth life.

Retirement for Cause (RFC) Concept

The NDI and Proof-Load Testing approaches, employed for military engine disks, lead to the concept of "retirement for cause". This means, when the concept is adopted, that NDI or spin pit proof-loading can be repeated until, in the case of NDI, cracks are found; or in the case of proof loading, the disk bursts on test. This concept then, only requires retirement when there is a cause to do so (i.e. a known, detected crack).

This can be contrasted with the "safe life" method where 999 out of 1000 parts are retired based on a statistical probability of a crack, rather than its actual presence. Analysis and testing have proven that the vast majority of disks retired under the safe-life method have considerable, safe service-life remaining.

Within the military at the present time, the repeat NDI and spin pit proof-loading have not extended beyond the traditional LCF safe-life of the disks. The option to exercise the Retirement for Cause concept, extending the service life beyond the traditional LCF life, is at the discretion of the Force Commander.

References

1) Palmgren, A.: Die Lebensdauer von Kugellagern, Z.V.D.I. *68*, 339-341 (1924).

2) Minor, M.A.: "Cumulative Damage in Fatigue", J. Appl. Mech. 12, A159-A164 (1945).

3) Stone, M., and Swift, *T.:* "Future Damage Tolerance Approach to Airworthiness Certification", presented at 10th International Committee on Aeronautical Fatigue (ICAF), Brussels, Belgium, 17 May 1979.

PRIOR ROTOR FAILURES DUE TO SEGREGATION IN TITANIUM ALLOYS

This section summarizes the metallurgical investigations of reported Type I and Type II defects found in service, in titanium rotors. Twenty-five (25) metallurgical reports dating as far back as 1964, were submitted for review to the Titanium Review Team by four engine manufacturers.

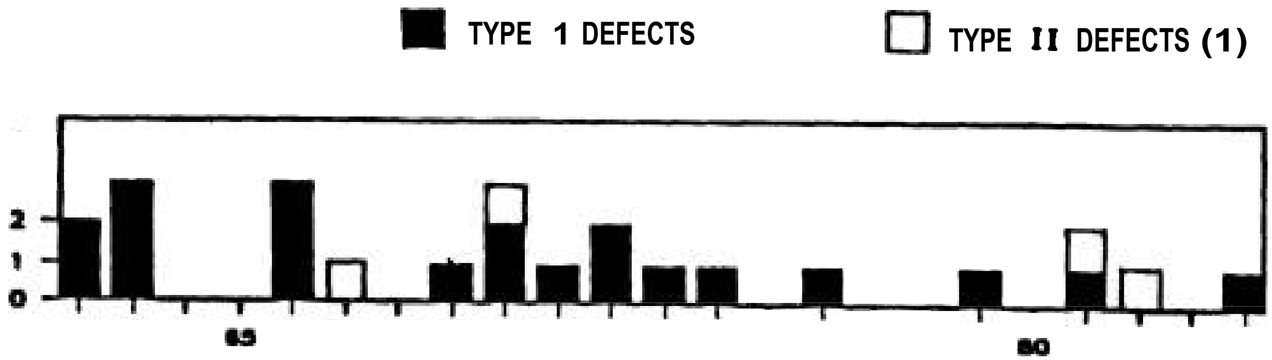
Rotor titanium alloys and processes described in the reports were much the same as described to the Review Team during visits to the various facilities. Some of the written metallurgical investigations were incomplete, and therefore, a definitive evaluation was not possible. However, in the first part of this section, general findings are drawn from the reports which specifically address the melting and billet manufacturing practices and the non-destructive inspection methods. The latter portion of this section addresses the metallurgical findings and their relationship with NDI detectability and fracture mechanics.

General Findings:

Figure 5.K.1 shows the number of rotors burst or cracked in service as compared to the year in which the heat (ingot which was used to make respective rotors) was melted. The fan disk involved in the Sioux City accident was melted in 1971. Even though improved production UT methods and improved process controls have been established, these Type I and II defects continue to plague in-service rotors. Most disks melted prior to 1970 have reached their service life limit and have been retired. Rotors produced in the early seventies are high time/cycle parts if not already retired. Even though the number of rotor failures is relatively small as compared to the thousands of disks in service, these few failures are unacceptable because they are the result of correctable, process control/quality problems, as determined by metallurgical analyses. These problems, unless corrected or greatly reduced, will result in additional failures.

Another trend that has been observed is illustrated in Figure 5.K.2. Rotors which were made from billet diameters greater than 8 inches accounted for 100% of the burst or cracked rotors caused by Type I defects. Rotors, which were made after 1970 from 16 " (inch) diameter billet, accounted for 80% of the burst or cracked rotors caused by Type I defects. Rotors made from small diameter billets have not been reported burst or cracked due to Type I defects. Several factors, such as: a lower number of engine flight cycles in service, improved UT inspectability in billet-form due to the smaller diametral size, and the increased amount of uni-directional working in the smaller billet, might contribute to this result.

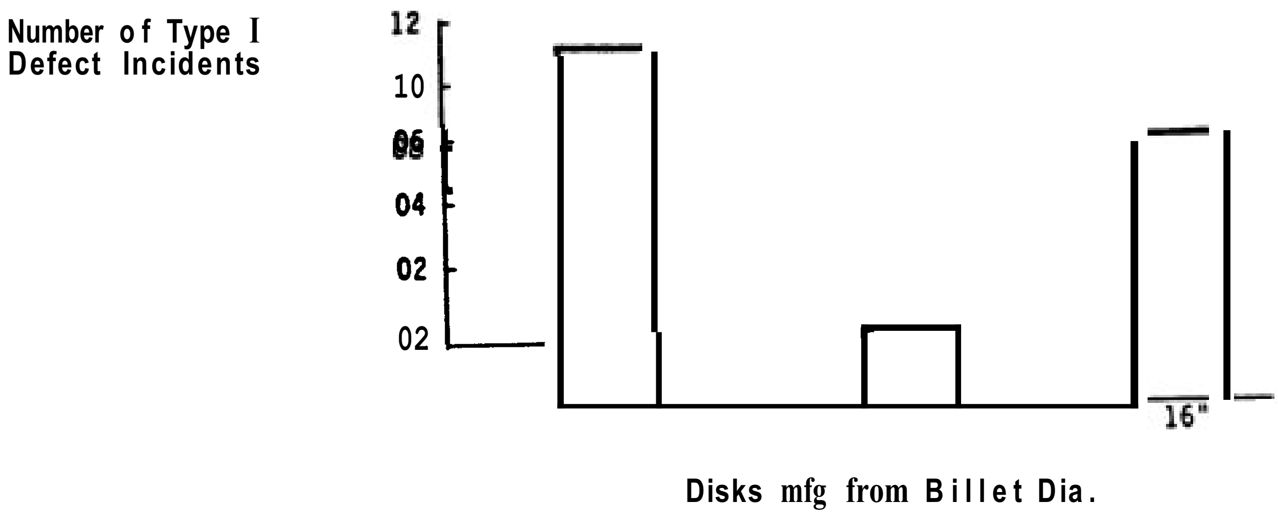
FIGURE 5.K.1



APPROXIMATE YEAR U.T. METHOD WAS INTRODUCED IN PRODUCTION	BILLET CONTACT U.T. 8/64" FBH (2) OR EQUIVALENT	(3) <-------->	BILLET IMMERSION U.T. 5/64' FBH OR EQUIVALENT	BILLET IMMERSION U.T. 3/64. FBH OR EQUIVALENT
	NO SONIC SHAPE U.T.	(3) <-------->	SONIC SHAPE IMMERSION U.T. NO. 1 FBH OR EQUIVALENT	
APPROXIMATE YEAR TRIPLE VAR WAS INTRODUCED IN PRODUCTION	DOUBLE VAR		TRIPLE VAR	

NOTE: (1) THE NUMBER OF ROTOR BURSTS AND CRACKS IS HIGHER THAN SHOWN
(2) FBM (FLAT BOTTOM HOLE) SIZE DEPENDENT ON BILLET DIAMETER OF TEST PIECE
(3) SOME MANUFACTURERS INTRODUCED IMMERSION U.T. AT DIFFERENT TIMES WITHIN THIS INTERVAL

DISKS MELTED AFTER 1962



DISKS MELTED AFTER 1970

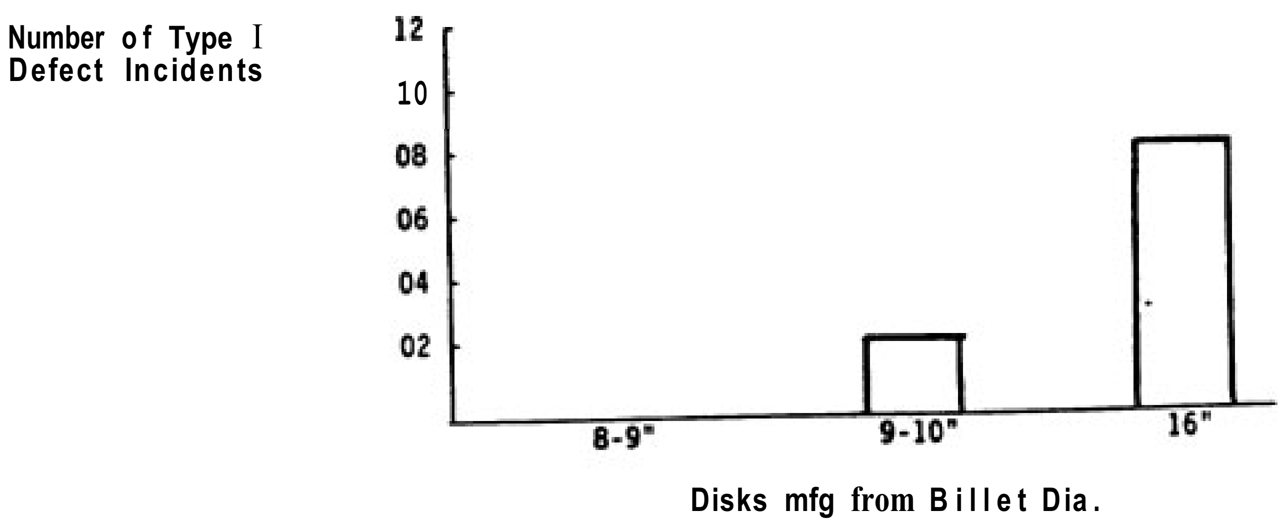


Figure 5.K.3 shows the number of burst and cracked rotors with respect to the defect location on the disk. The fact that most cracks originated and propagated from defects located in the bore, can be explained by the bore having the highest stress throughout a large volume of material (i.e. the highest bulk stress). This high stress, in the presence of a defect, will initiate and propagate a crack to the surface where it will either be detected or may cause burst. Cracks have propagated from defects in the web, only when the segregation is in a critical location and/or orientation, or if the segregation stress concentration is severe. Approximately 80% of the burst or cracked rotors with defects shown in Figure 5.K.3 were from subsurface defects. All of these subsurface defects propagated to the surface in low cycle fatigue, except one, which was detected by UT. In view of this data, the Review Team believes that better surface and subsurface NDI of in-service rotors will result in significantly improved safety.

Metallurgical Findings:

The microstructure and physical characteristics around a Type I or II titanium defect varies with the cause which created this anomaly. Figure 5.K.4 describes titanium defects in four categories. Each defect category has a characteristic microstructure and chemistry as related to its fracture topography (fractography) and physical properties. Also discussed will be: the frequency of defect type occurrences as found in burst or cracked rotors, relative detectability by current NDT methods, and the relationship between a crack and a Type I or II defect with regard to fracture mechanics.

Nitrogen (N_2) concentrations have been quoted from various reports, and it appears that, depending on the nitrogen analysis method and specific area of analysis, wide variations occur. This report refrains from using the values casually, and refers to them only if the analysis method and exact zone were reported.

Category 1

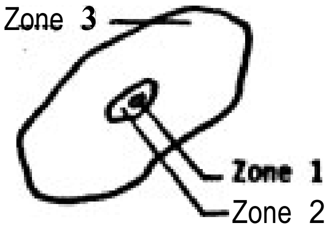
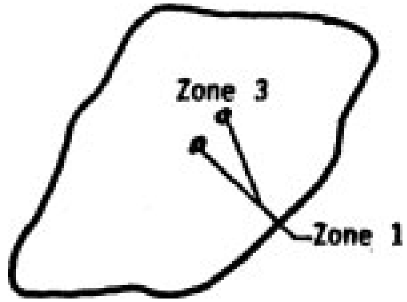
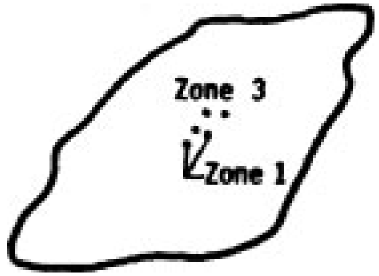
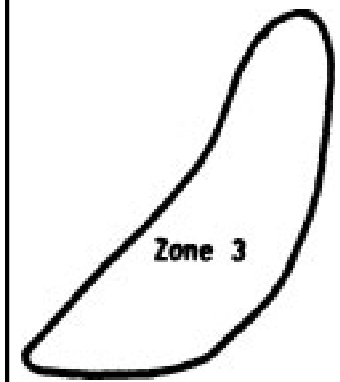
In the case of Category 1, a typical micrograph of this Type I defect or HID is shown in Figure 3.D.1 (top). This photo is illustrated in Figure 5.K.4 under Category 1 and is depicted with three distinct zones. In Figure 3.D.1, Zone 1 is an elliptically-shaped void, .045" wide by .025" high, with irregular surfaces. Based on the review of other Category 1 defects, the three dimensional shape would probably be an ellipsoid. The average void's volumetric size for the reports reviewed was equivalent to a .030" diameter sphere. Size and orientation of the defect are significant factors which have affected ultrasonic detectability. The ellipsoid shape and rough

FIGURE 5.K.3

Location of Type I Defect	Number of Rotors With Defects	Number of Incidents of Cracked Rotors	Number of Incidents of Burst Rotors
BORE	13	6	7
WEB	5	3	1
WEB HOLE (Or Counterweight Hole)	3	2	1
SPACER ARM	1	0	0
UNKNOWN	1	0	0

FIGURE 3.K.4

TITANIUM ROTOR FAILURES CAUSED BY MATERIAL DEFECTS

	Type I Defects		Type II Defects	
	Category 1	Category 2	Category 3	Category 4
Metallurgical observations (typical)	-Nitrogen stabilized hard alpha zone (zone 2) encasing large spongy-appearing void (zone 1) -Alpha case surrounded by enlarged or blocky alpha grains or platelets (zone 3) 	-Small or no voids (zone 1) -No hard alpha tone -Large area of nitrogen stabilized enlarged & enlongated alpha grains or platelets (zone 3) 	-Microvoids (zone 1) -Low or no elevated N_2 or O_2 concentration -Large area of aluminum stabilized enlarged & elongated alpha grains or platelets (zone 3) 	-Pure elemental segregrtlon of pure Ti or Al (zone 3) 
Zone hardness	-Zone 2 = Rc 65-80 -Zone 3 = Rc 55-70	Rc 45-65	Rc 35-45	Rc 12
Zone shape	All Zones Ellipsoid Shaped as Per the Direction of Work			
Host probable cause	Burnt sponge	Contaminated weldment or contami nated revert mater1al	Drop-1n	Improperly melted/ homogenized alloy or plpe
Defects In 22 in-servlce disks	41%	41%	14%	4%

Increasing difflculty to detect by ultrasonic testing →

Increasing probabIllty that Improved melting homogeneity will eliminate defects →

surface condition would contribute to making UT detection more difficult. The Review Team is not aware of any reliable UT detectability information regarding the size of these type voids in billets and rotor sonic shapes.

Zone 2, which is the white (primary alpha) capsule wall, encases the void and includes the spongy appearing material. Several reports, written in the early 1970's have noted similar sponge-like material in defects with high concentrations of N_2 particularly. This N_2 is probably in the form of TiN, a refractory material which melts at 2930°C (5305°F) and, during VAR, diffuses very slowly into the matrix material forming a white encasement of nitrogen stabilized alpha phase. In several reports, this uniformly shaped alpha case, as shown in Figure 3.D.1 (top), did not exist; however, hard, nitrogen enriched, spongy-appearing particulates were evident. It is believed that high temperature diffusion and deterioration of this white hardened case occurred and its constituents dispersed into matrix material as shown in Figure 5.K.5. Zone 2 microhardness values were equivalent to R_c 65-80, with N_2 concentrations around 1.5% as determined by microprobe analysis. Also, microcracks were revealed around the periphery of the void in all directions. It is believed that the forging operation can cause microcracking of this embrittled zone which has been characteristic of all Category 1 defects. Even though microcracking can improve UT detectability, it can also create stress raisers from which cracks can propagate into the matrix material. Macroscopically, close to zone 2, the fracture surface was described as a shiny, large, brittle-appearing area corresponding to a predominantly cleavage fracture.

Zone 3 was shown as a region of coarse elongated or sometimes blocky alpha grains or platelets. Microhardness measurements in this alpha stabilized area ranged from R_c 55-70, while N_2 concentrations ranged from .03 - .6% when measured by microprobe techniques. The scanning electron microscopy (SEM) characteristics of the fractured surface in this zone were described as having areas of fatigue (striations) in addition to cleavage and intergranular cracking. This area was interspersed with occasional local islands of brittle fracture (cleavage), and ductile fracture features with irregular patches of low cycle fatigue striations. Due to interspersed areas of cleavage and ductile tearing, within the fatigue progression, accurate striation counts could not be made. Farther from the defect, where hardness values decreased, the fatigue portion of the fracture path was transgranular with normal fatigue progression.

After reviewing many metallurgical analyses, it appears that Category 1 defects have not been a cause of rotor failure since

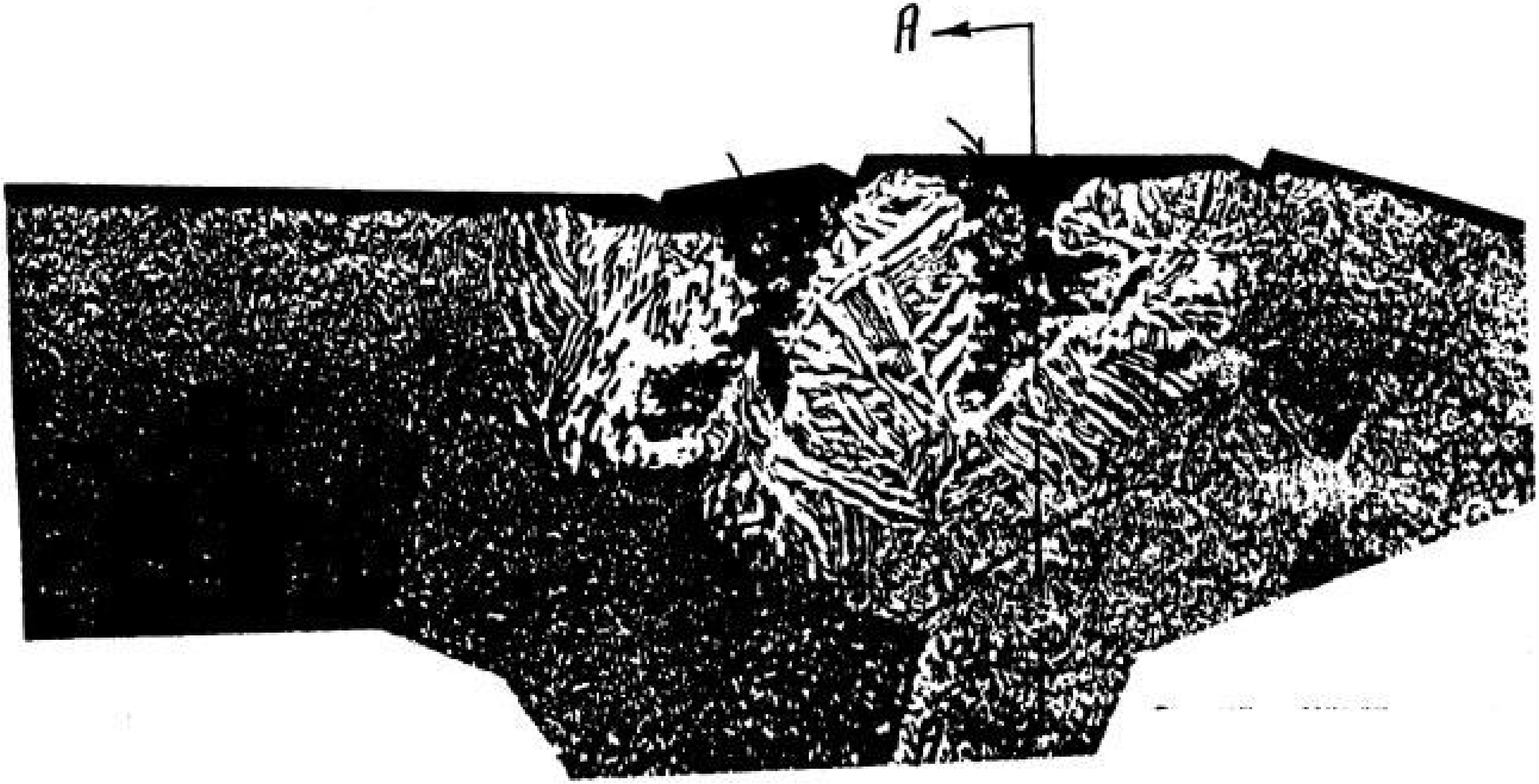


FIGURE 5.K.5 13x

Collage of micrographs showing a Type I/Category 1 defect showing diffused nitrogen stabilized columnar alpha grains. Partlally intact white alpha case surrounds two sponge-filled voids.

melts made in the early 1970's. A possible exception to this was one rotor failure which, because of the unusual metallurgical characteristics, could not be positively excluded as a Category 1 defect. Overall, it is possible that UT has been effective in detecting and eliminating the larger voids, but a careful reliability assessment would be required to determine this.

Category 2

Burst or cracked titanium rotors identified as Category 2 were characterized as having small voids (Zone 1), or no voids, surrounded by a nitrogen stabilized alpha phase (Zone 3). A micrograph of this type defect is shown in Figure 3.D.1 (bottom). This photo is illustrated in Figure 5.R.4 under Category 2, and is depicted with two distinctive zones.

Voids were generally much smaller in Category 2, than in Category 1. For Zone 1, the average void size was equivalent to a .005" diameter sphere which is approximately 400 times smaller than voids in Category 1. Voids on the fracture surface, and internally within abnormal microstructure, ranged in size from .0003" diameter to .040" diameter. In only one report, microporosity was not noted, nor could microporosity be seen in the SEM fractographs or micrographs. Zone 2 features, as described in Category 1, did not exist.

Macroscopic examination of the fracture surface (Zone 3) for Category 2 rotors showed smooth, brittle features, with areas of cleavage-like characteristics close to the origin (in some reports this area of'cleavage fracture is considered the origin). A typical SEM fractograph of this Zone 3 area is shown in Figure 5.K.6. These cleavage planes at high magnification using transmission electron microscopy (TEM), revealed irregular patches of high density striations as shown in Figure 5.K.7. Farther from the origin, fatigue striations and ductile tearing were found in some areas between brittle fracture regions. Microscopic analysis of sections through the fatigue origins showed large areas of interstitially stabilized alpha segregation. In some cases, where microhardness and nitrogen values were high, the heaviest concentration of enlarged alpha microstructure exhibited a network of fine, brittle appearing "craze" cracks. The propagation of this network of cracks would progress through twinned crystals and intergranularly. Secondary cracking was seen emanating from the "craze cracks" and extending parallel to the primary fracture-surface which lay normal to the plane of maximum stress.

In conjunction with the micro-voiding observed in most Category 2 failures, .large areas of abnormal, nitrogen stabilized, enlarged, alpha microstructure was evident. This microstructure was the

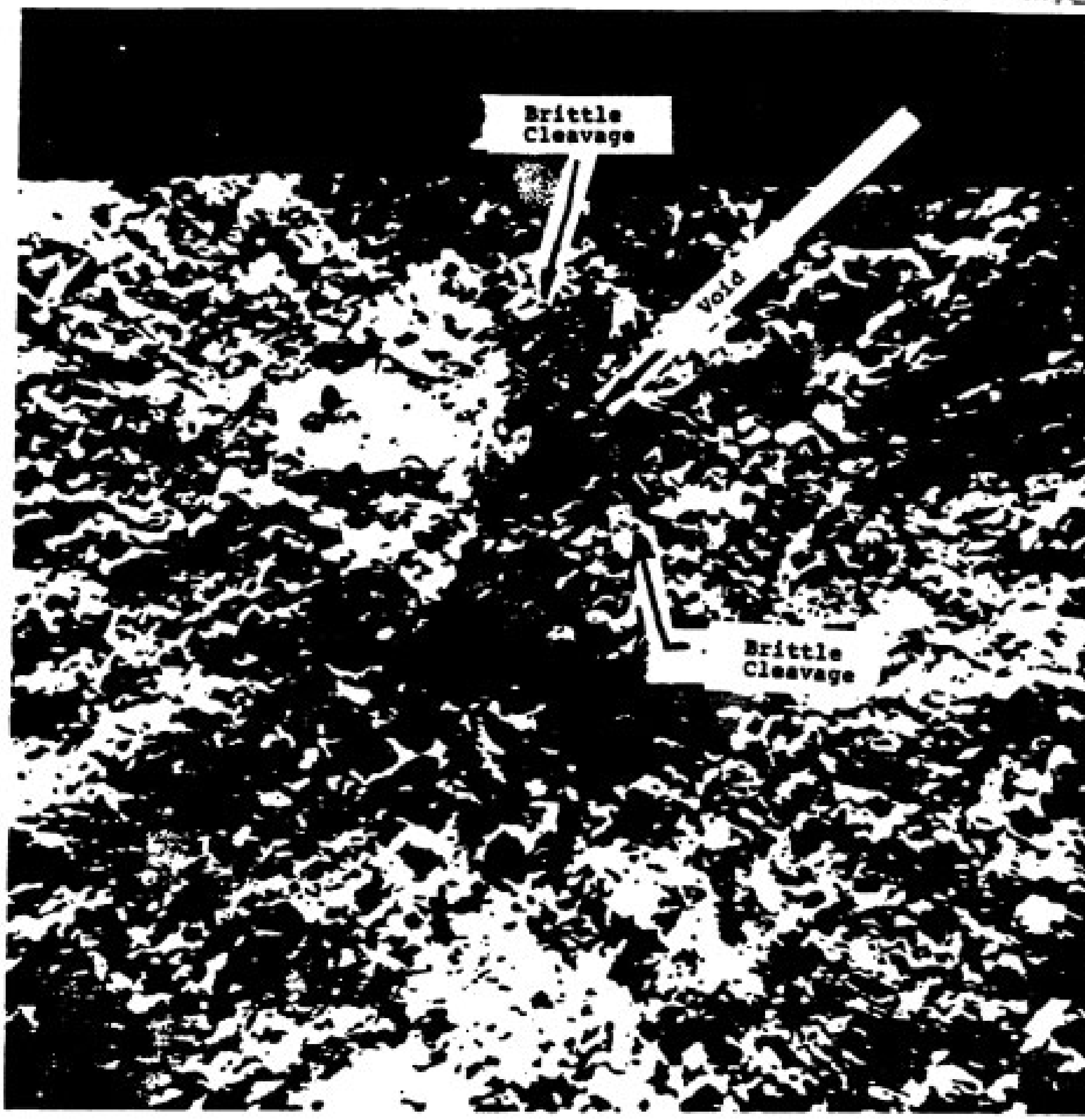


FIGURE 5.K.6 200x

Typical scanning electron microscope (SEM) frrctograph of a Type I/Category 2 fracture origin. Around a void (arrows) predominately brittle, cleavage-like features were reported. Farther away from this site interspersed areas of cleavage with areas of fatigue and ductile tearing.

FIGURE 5.K.7 5800X

Transmission electron microscopy photograph showing irregular patches of high density striations, typical of cleavage corresponding to shiny brittle appearing region at crack origin.

predominant feature at the fracture origin which was aligned normal to the plane of highest stress. On average, the interstitially stabilized microstructure of Category 2 defects (.018 in.^{3}) was 16 times larger than the nitrogen stabilized microstructure seen in Category 1 defects (.00114 in.^{3}). In addition, to initiate cracks from small, clean, subsurface voids requires very high stresses which are unrealistic, and two reports referenced the use of fracture mechanics to analyze these failures. Coupled with the most pessimistic assumptions of crack propagation rates (includes dwell time), the report deduced that a much larger defect than the void caused propagation to occur. The size of the initiation site predicted to cause propagation is equivalent to the fracture zone which revealed cleavage predominantly.

In cases where these large areas of alpha stabilized segregation extended to the surface, failure investigations showed that acid etching could reveal the segregation; however, the in-line production inspection failed to detect this unacceptable microstructure. Moreover, it is suspected that most current production UT methods do not have the capability of detecting any Category 2 size voids (maximum size reviewed was .062" X .036"), while the best state of the art UT system would probably miss seven of the nine Category 2 size voids reviewed (these seven were equal to or smaller than .010" in size).

Cateaorv 3

Category 3 defects were similar to Category 2 defects in fractographic and metallographic appearance. As shown in Figure 5.K.4, the Category 3 defect is illustrated with two zones. Small micro-voids (Zone 1), which ranged in size from .0002" to .011" in length were found within the surrounding coarser grain material. The elliptically-shaped voids were few in quantity, well dispersed, and detectable by SEM analysis on the fracture surface. The voids were virtually free of any particulate major alloying material. Zone 2 features, as described in Category 1, did not exist.

Zone 3 revealed fractographic features reflecting the underlying microstructure. In all reports, primary failures or cracks developed from cleavage around microvoids. Inner Zone 3 areas were described as brittle-appearing cleavage bands, and outer areas of quasi-cleavage interconnected by small areas of ductile tearing, with intermittent and LCF fatigue striations. One report described the brittle reflective cleavage as developing through aligned alpha colonies, and usually changed direction with a change in orientation of the platelets. On the outer areas of the origin where alignment of alpha grains was not distinguishable, the fracture was irregular, and revealed a noncrystallographic growth pattern in order to link-up with neighboring facets. The area of the fracture surface, depicted of Zone 3 segregation, was averaged at 1.7 in.^{2}, and correlated with the underlying abnormal microstructure. Beyond the Zone 3 fracture surface, the fatigue propagated transgranularly, through normal metal, until disk burst.

The discriminating characteristics between the Category 2 and 3 defects were in microhardness and in chemistry. Microprobe analyses showed aluminum-rich alpha phase concentration with no reported increases in nitrogen in the traverses made through the origin. Similar traverses performed with the microhardness tester showed no significant increase in hardness. In one report in which beta segregation was observed, an EDAX traverse showed a deficiency in aluminum and zirconium which correlated very closely with a decreasing microhardness gradient.

There have been additional Type II defect failures which have not been reported in Figure 5.K.1. A separate FAA review would be required to determine frequency, and similarity to the reports submitted; but this is probably not necessary given this current Titanium Rotating Components Review.

Cateaorv 4

Category 4 defects show only one zone of abnormal microstructure (Zone 3), as illustrated in Figure 5.K.4, which may be produced by pure elemental segregation or "pipe". In a case of pure titanium segregation, zone 3 revealed microhardness measurements as low as R_c 12. Within the origin, no porosity nor cleavage was evident, however, law cycle fatigue striations covered by an oxide layer was predominant. Cracks initiated and propagated from multiple sites at various depths within the material, creating a ratcheted tunnel effect. The microstructure was characteristic of titanium exposed, to temperatures beyond the beta transus, during forging. Large columnar grains grew from multiple nucleation sites, creating a basketweave structure. Farther from the defect, the fatigue propagated transgranularly, through normal metal, until the disk burst.

In the early development of titanium production, pure aluminum segregation or "pipe" was of concern, prior to the introduction of "hot topping". Since this improvement, there have been ho recent incidents; therefore, these reports were not requested from the engine manufacturers, and have not been included in Figure 5.K.4.

Category 4 defects have the smallest incident rate, and can be eliminated the easiest, by improved process controls, i.e. by removing any risk-of-contamination melt procedures and macroetching every finish-machined rotor. On the other hand, these type defects are most difficult to detect by UT because of the absence of voids or cracks.

Summary:

In this section (on prior rotor failures due to segregation in titanium alloys), various stages of crack growth for Types I and II defects have been observed, which are:

1. Void cracking,

2. Smooth cleavage, immediately around the void, corresponding to brittle microcracking,

3. Intergranular facet cracking, along alpha plate colonies, and

4. Low cycle fatigue and ductile tearing, between facets.

Depending on the Category of defect, certain stages are more influential in crack propagation than others. For example, in Category 1, the void was the predominant factor in crack propagation, i.e., size, shape, orientation, and location (stress field). However, in Categories 2 and 3, microstructure around the void was an equally, or more, important factor in crack growth rate. Crack growth rate in the abnormal microstructure was influenced by the same factors which influenced the void, with the addition of chemistry. It was reported that increased levels of nitrogen, oxygen, and aluminum can also be detrimental to fatigue properties. It is clear that fracture analysis based on the void size alone (assuming the void as a crack), can be overly optimistic. Therefore, substantial conservatism should be used when equating a voided, subsurface Type I or II defect to a crack.

In reviewing the rotor incidents described in Figure 5.K.1, the rate of Category 1 defects which have caused rotor cracks or separations, has decreased. And, the rate of Category 2, 3, and 4 defect bursts or cracks, has not increased. It is believed that with the current manufacturing processing and NDI methods, the rate of Category 2, 3, and 4 failures will decrease only slightly. Also, it is believed that improved NDI systems in rotor production, could significantly decrease the existing rate of Category 1 and 2 defects: and improved material processing methods could significantly decrease the existing rate of all defect Categories. Therefore, at least until improvements are demonstrated to greatly reduce the defect rate, additional surface and subsurface in-service inspections are recommended for all titanium rotors.

Results

1. In earlier times of titanium production, pure aluminum segregation pipe was a major problem: but since the development of improved "hot topping" techniques, there have been no further service incidents attributable to that kind of defect.

2. Types I and II defects continue to plague recent production titanium rotors.

3. Rotors which were made from billet diameters greater than 8" accounted for 100% of the failed rotors caused by Type I defects. Rotors, which were made after 1970 from 16" diameter billet, accounted for 80% of the failed rotors caused by Type I defects.

4. Most defects were found in the bore. Approximately 80% of the failed rotors with defects were caused by subsurface defects. All of these subsurface defects propagated to the surface in low cycle fatigue, except one, which was detected by UT.

5. Category 1 defects' size and orientation are significant factors which have affected ultrasonic detectability. The ellipsoid shape and rough surface condition would contribute to making UT detection quite difficult.

6. With some Category 1 defects, accurate striation counts could not be made, due to interspersed areas of cleavage and ductile tearing, within the fatigue progression zone.

7. Category 2 voids were approximately 400 times smaller than voids in Category 1. Voids on the fracture surface, and internally within abnormal microstructure, ranged in size from .0003" diameter to .040" diameter. In only one report, microporosity was **not** noted, nor could microporosity be seen in the SEM fractographs or micrographs.

8. In conjuction with the micro-voiding observed in most Category 2 failures, large areas of abnormal, nitrogen stabilized, enlarged, alpha microstructure was evident.. On average, the interstitially stabilized microstructure of Category 2 defects, was 16 times larger than the nitrogen stabilized microstructure seen in Category 1 defects.

9. In cases where these large areas of alpha stabilized segregation intersected the surface, failure investigations showed that acid etching could reveal the segregation; however, the in-line production inspection failed to detect this unacceptable microstructure.

10. Depending on the Category of defect, certain stages of crack growth are more influential in crack propagation than others. In Category 1, the void was the predominant factor in crack propagation, i.e. size, shape, orientation, and location (stress field). In Categories 2 and 3, microstructure around the void was an equally, or more, important factor in crack growth rate.

11. It was reported that moderate levels of nitrogen, oxygen, and aluminum can be detrimental to fatigue properties.

12. In view of the rotor incidents described in Figure 5.K.1, the rate of Category 1 defects which have caused rotor cracks or separations, has decreased.

13. The rate of Category 2, 3, and 4 defects which have caused failures, has not increased.

<u>Concerns</u>

1. Types I and II defects are the result of process control/quality problems which, unless corrected or greatly reduced, will probably result in additional failures.

2. Rotors which are made from billets greater than 8" in diameter, are more likely to have undetected Type I defects.

3. At least until NDI systems and material processing methods are improved, and subsequently demonstrated to greatly reduce the defect rate, additional surface and subsurface in-service inspections are believed necessary for all titanium rotors.

4. After reviewing many metallurgical analyses, it appears that Category 1 defects have not been a cause of rotor failure since melts made in the early 1970's. A possible exception to this was one rotor failure which, because of the unusual metallurgical characteristics, could not be positively excluded as a Category 1 defect. Overall, it is possible that UT has been effective in detecting and eliminating the larger voids, but a careful reliability assessment would be required to determine this,

5. To initiate cracks from small, clean, subsurface voids requires very high stresses which are unrealistic. However, with the use of fracture mechanics to analyze prior failures, coupled with the most pessimistic assumptions of crack propagation rates, a report deduced that a much larger defect than the void caused propagation to occur.

6. Most current production UT methods probably do not have the capability of detecting any Category 2 size voids smaller than .062" X .036", while the best state of the art UT system would probably miss seven of the nine Category 2 size voids reviewed (these seven are equal to or smaller than .010" in size).

7. Fracture analysis based on the void size alone (assuming the void as a crack) can be overly optimistic. Therefore, substantial conservatism should be used when equating a voided, subsurface Type I or II defect to a crack.

8. With the current manufacturing processing and NDI methods, the rate of Category 2, 3, and 4 failures will decrease only slightly. (But improved NDI systems in rotor production could significantly decrease the existing rate of Category 1 and 2 defects, and improved material processing methods could significantly decrease the existing rate of all defect Categories.)

SECTION 6

FINDINGS

The Titanium Rotating Components Review Team has considered all pertinent information collected during the facility visits, and makes the following findings relative to the design, manufacture, and inspection of titanium-alloy critical rotating components. In general, the individual findings are applicable to more than one engine manufacturer and/or his supplier(s), if not most, and should not be interpreted as comment on any individual company.

PROCESS CONTROL:

1. Since the early 1970's (when the Sioux City accident-disk was made) improvements have been continuously incorporated in the titanium manufacturing processing and inspection areas. Turbine engine manufacturers and the titanium industry have significantly improved titanium disk quality over the past 20 years; and major improvement efforts are continuing.

2. Scrap material (revert) is a potential source of contamination (HDI's and oxynitrides) in titanium ingot production. While the engine manufacturers' specifications permit the use of revert, there is no melt industry standard nor engine manufacturer's criteria for controlling the conditions under which revert may be used in premium quality ingot.

3. Consumable electrode vacuum arc melting has been the standard for ingot production for more than 20 years. While many improvements have been introduced during this period, the last single improvement of major significance was the introduction of triple melting in the early 1970's.

4. Some engine manufacturers do not exercise the high degree of process control on raw material suppliers (i.e. the sponge, revert, and ingot sources) as do other engine manufacturers. This function is usually delegated by the former to the forgers.

NEW MANUFACTURING PROCESSES:

1. Three new technologies are emerging Japanese in the production of titanium. These are: the vacuum distillation finishing process and the electrolytic reduction process, for elemental titanium; and cold hearth melting (CHM) for ingot.

MANUFACTURING INSPECTION:

1. Today's production (and in-service) NDI techniques do not consistently detect titanium metallurgical defects.

2. Retention requirements for inspection and processing records in the manufacture of critical components are established by the certificated manufacturer's record retention schedule, and are currently 20-35 years depending on manufacturer. The retention schedule is FAA approved as part of the certificated manufacturer's quality procedures.

3. When one or more defects are found at billet ultrasonic inspection, typically the entire heat (ingot) is down-graded from premium to standard grade (i.e. rotating to non-rotating grade). Prior to this practice, defects were removed by cropping only the affected lengths of billet.

4. When one or more defects are found at rectilinear disk (ultrasonic) inspection, or at the disk segregation-etch inspection, typically only that disk(s) is scrapped and only the adjacent disks from the ingot are over-inspected (i.e. carefully re-inspected). Usually there is no effort made to reinspect all disks from the same ingot, nor to trace material from the same ingot which may have been sold to other engine manufacturers.

SERVICE EXPERIENCE:

1. All of the 6 turbine engine manufacturers visited, plus the 3 which were contacted by telephone, use titanium disks in the fan and/or compressor section of their commercial engines.

2. Of the six engine manufacturers visited, four have had a combined total of 25 cracked or burst titanium disks occur in commercial service due to metallurgical defects. Based on our review of manufacturing procedures/process controls, lifing methods, stress levels, inspection procedures, and cycles accumulated, the lack of in-service failures at the other two engine manufacturers is probably due to an insufficient number of (total fleet) engine flight cycles in service.

3. The rate of failure of titanium disks has decreased over the last 20 years. (As a rough indication of this trend, the following statistics are readily available. For the years 1962 thru 1975, the rate of uncontained transport category engine failure, due to disks and spacers of all materials,

is 0.374 per million engine hours. The comparable rate for the years 1976 thru 1983 is 0.228 per million engine hours, a decrease of 39.0%.)

DESIGN PROCEDURE:

1. Most engine manufacturers do not have a formal design procedure to account for the adverse effect of metallurgical defects on the safe life of titanium disks. That is, typically, once approved by manufacturing inspection, disks are effectively assumed to be defect-free from a design structural analysis standpoint.

SECTION 7

CONCLUSIONS

Based on a review and analysis of the data collected, the Titanium Rotating Components Review Team makes the following conclusions concerning the design, manufacture, and inspection of aircraft turbine engine titanium disks, hubs, and spools. In general, the individual conclusions are applicable to more than one engine manufacturer and/or his supplier(s), if not most, and should not be interpreted as comment on any individual company.

GENERAL:

1. Quality in aircraft turbine engine titanium disks has relied on stringent design and manufacturing process controls, backed up by destructive and non-destructive inspection techniques. Although the industry has made significant progress since the early 1970's to ensure the quality of titanium alloy disks, further improvement is needed in all 3 of these areas (i.e. design, manufacturing process control, and NDI), and advancement toward defect-free material should be accelerated.

2. There are several areas (in design synthesis, manufacturing process control, and NDI) where improvements can be made in the production of titanium disks, hubs, and drums. Some procedures may be traded-off if compensating improvements are made in other places. Also, new technologies may completely replace certain procedures in the process. Therefore, the recommendations in this report may not necessarily constitute the only or best way to move closer to zero metallurgical defects and the desired level of disk structural integrity. This can best be determined by the engine companies respectively working together with their customers, with all tiers of their titanium suppliers, and with the FAA.

MANUFACTURING PROCESS CONTROL:

1. The criteria for the evaluation and use of scrap in the melting process are not adequately controlled.

2. Chips or machine turnings if properly processed can be used to produce premium grade ingot. This processing should include at least a complete chemical analysis using continuous sampling, air separation and high intensity magnets used to separate HDI's and magnetic materials, continuous sampling for oxygen and carbon content, and 100% X-ray inspection.

3. The manufacture of titanium rotating components is sensitive to the generation of defects at several stages in the process (e.g. sponge production, welding, melting, etc.).

4. Further improvements, such as quadruple melting, to current triple vacuum melt process technology would not appear to substantially increase the probability of reducing the size of or eliminating defects.

5. There is need for stricter housekeeping (cleanliness) procedures in the sponge and ingot production stages of titanium disk manufacture.

6. Finer particle-size titanium sponge, based on tests conducted by at least 2 sponge producers, results in fewer LDI's surviving the VAR process. That is, fewer survive DM (double melting), and still fewer survive TM (triple melting).

7. The use of vacuum distillation finishing for the purification of titanium sponge, appears to result in a significantly higher purity product than the traditional purification method (acid leaching). Japanese development - Tmt in this Country

8. The cold hearth melting process, either electron beam or plasma arc, shows promise of providing significant improvement in minimizing or eliminating defects during the melt stage.

MANUFACTURING INSPECTION:

1. All of the disks from the same ingot should be over-inspected when one or more defects are fount at rectilinear disk (ultrasonic) inspection or at the disk segregation-etch inspection.

2. Defects much larger than 1/64 inch in size (about the smallest that can be regularly detected) have slipped through the inspection system either thrcugh human error or equipment limitations.

3. The titanium disk industry's new defect reporting/alerting organization, called the Jet Engine Titanium Quality Committee (JET QC), is off to a good start and is supported by the FAA Titanium Review Team as one of the potentially most effective vehicles for improving titanium metallurgical quality and disk structural integrity.

DESIGN PROCEDURE:

1. Analytical methods employed by engine manufacturers to establish safe operating lives for rotating engine components do not deterministically account for the maximum flaws which may be missed by current initial inspection methods. However, attempts are made by one or two manufacturers to reduce the probability of failure by utilizing joint-probability (e.g. Monte Carlo) methods based on distributions of expected flaws combined with material variability (probabilistic approach).

   The difficulties encountered which make a deterministic approach currently unviable arise in the detection of embedded hard alpha Type I flaws. If the hard alpha is associated with a void, then the probability of detection using current initial inspection methods may be high. On the other hand, embedded hard alpha free from voids and cracks, can not be detected by current inspection methods.

   Thus, to account for the size of all possible embedded hard alpha inclusions in a deterministic way currently appears to be unfeasible either from an initial inspection standpoint or from an in-service inspection frequency standpoint. However, in the case of surface flaws, and even embedded flaws which may propagate to the surface prior to failure, there appears to be a case for safety improvement by periodic in-service inspections.

SECTION 8

RECOMMENDATIONS

: Titanium Rotating Components Review Team makes the following :ommendations to the Engine and Propeller Directorate, Aircraft rtification Service, for the improvement of titanium :tallurgical quality and disk structural integrity. In general, ie individual recommendations are applicable to more than one ngine manufacturer and/or his supplier(s), if not most, and should not be interpreted as comment on any individual company.

MANUFACTURING PROCESS CONTROL:

1. Initiate steps to improve the titanium sponge production and inspection processes to reduce the occurrence of burnt sponge.

2. Limit the use of revert (scrap) material in triple vacuum arc remelt (VAR) premium grade titanium alloys to only turnings (chips) and premium grade solids.

3. Allow only triple VAR, or one of the new cold hearth processes, as standards for premium grade material. Any process used, must be better than or equal to the triple VAR process in terms of defect size and number of defects per million pounds of titanium melted.

4. Require ingot descaling processes to remove surface material down to clean, sound metal prior to remelting.

5. The industry should accelerate the development of the cold hearth melting (CHM) process, with the goal of using CHM as the final melt for premium grade material.

6. The use of bulk weldable materials, to produce premium grade ingot exclusively by the VAR process, should only be allowed if all of the following occur:

   (a) All welding is performed in a vacuum chamber in an inert atmosphere under controlled conditions;

   (b) no unprocessed flame-cut material is used:

   (c) the alloy composition is known;

   (d) the material was not rejected from an ingot, billet, or finished product due to NDI indications; and

   (e) the material shall have been previously processed for use in premium quality material, titanium parts.

7. Require the engine manufacturers to revise their specifications to provide specific, detailed criteria on the use of scrap material in the production of premium grade titanium alloys,

8. Increase the engine Production Certificate holder's manufacturing inspection surveillance of sub-tier suppliers making raw material and forgings for critical life-limited parts.

MANUFACTURING INSPECTION:

1. Require etch (blue etch anodize or equivalent) inspections to be performed on finish-machined parts to ensure the optimum opportunity to detect segregation.

2. For UT of billets and semi-finish-machined disks, engine manufacturers should require the highest standard (smallest flat-bottomed hole (FBH) or equivalent) practicable in the industry for the size of part being inspected.

   The following levels are considered to be practicable: 1/64 inch diameter FBH for billet ≤ 5 inches, 2/64 FBH for billet > 5 but ≤ 10 inches, and (staying with) 3/64 FBH for billet > 10 inches. All semi-finish-machined disks (sonic shapes) should be inspected to a 1/64 FBH (or equivalent).

3. Require the use and retention (according to the engine manufacturer's FAA-approved records retention schedule) of UT scan, strip charfs or electronic equivalent for both billet and rectilinear, semi-finish-machined disks.

IN-SERVICE INSPECTION:

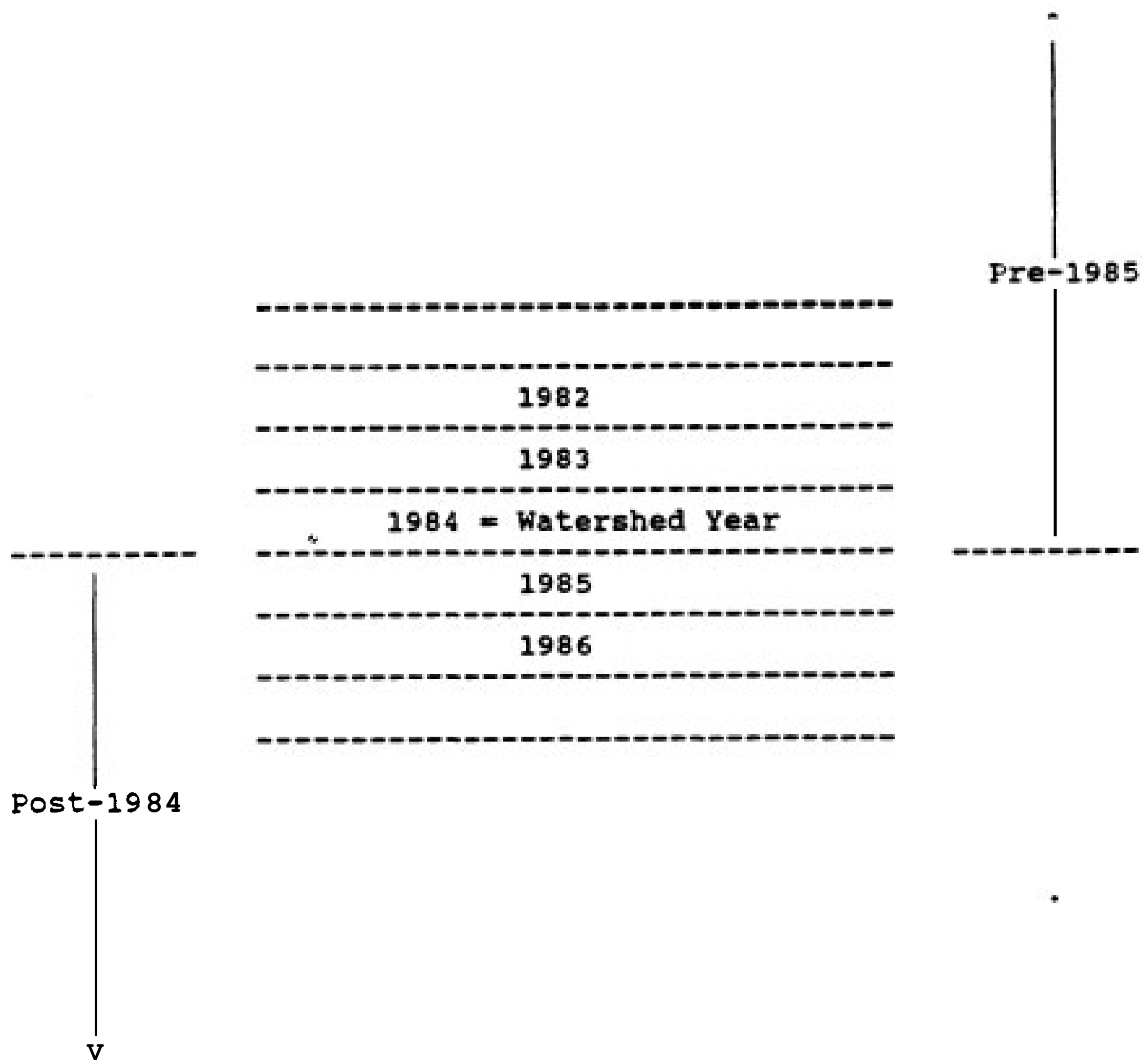
Pre-1985 Melted Material:

1. In the near term, for parts already in service, supplement the engine shop manuals' required fluorescent penetrant inspections with an eddy current inspection of the most critical (highest stressed) areas, whenever the engine is disassembled sufficiently to afford access to a major rotating part (inspections of opportunity).

. As a longer-term interim measure for parts already in service, require, in addition to the enhanced surface inspection, a subsurface inspection (e.g. ultrasonic) at least twice during each component's certificated cyclic life, at intervals acceptable to the Administrator.

FIGURE 8.1

Graphic showing time-line marking a major change in the quality of titanium alloys used in turbine engine, major rotating parts.



3. Develop criteria, within 2 years, to inspect all critical, life-limited, in-service parts at intervals established by fracture mechanics technology.

Post-1984 Melted **Material:**

4. Same as item 1, above. 6-12 MO.

5. Same as item 2, above. 18-24 MO.

6. Develop criteria, within 3 years, to inspect all critical, life-limited, in-service parts at intervals established by fracture mechanics technology.

DESIGN PROCEDURE:

1. Retain the current practice of retiring critical parts at pre-determined cyclic lives.

2. Require life management methodologies to consider the effect of metallurgical defects on part life, accounting for the maximum defect sizes which may be missed during production and in-service inspections.

3. Consider convening, within about 6 months, an industry-wide fracture mechanics/damage tolerance, NDI, and probabilistic/deterministic risk management Conference (or other suitable forum) to discuss the incorporation of damage tolerance concepts in commercial engines.

RESEARCH AND DEVELOPMENT:

1. Institute an FAA-funded aggressive (short term) research & development program to establish industry-wide probability of detection (POD) curves for fluorescent penetrant, ultrasonic, and eddy current, manufacturing and in-service inspection methods and processes. This POD data should include the effects of various surface treatments, such as shot peening, which tend to obscure cracks or defects.

2. A national standard should be developed to identify minimum qualifications and required training and examinations, for NDI personnel at all levels of expertise. Also, for the standard to be effective, industry-wide certification of NDI personnel should be required.

3. The JET QC (Jet Engine Titanium Quality Committee), with the concurrence of the FAA, should establish a uniform requirement for the percentage of each sponge lot required to be visually inspected, for premium quality sponge.

FAA POLICY AND GUIDANCE:

1. Develop new advisory material on lifing analysis and life management procedures for engine life-limited parts.

SECTION 9

TITANIUM ROTATING COMPONENTS REVIEW TEAM FACILITY VISIT SCHEDULE

FACILITY	VISIT DATES
Pratt & Whitney Division United Technologies Corporation 400 Main Street East Hartford, Connecticut 06108	December 11 & 12, 1989 and subsequent dates
Wyman-Gordon Company 244 Worcester Street North Grafton, Massachusetts 01538	December 13 & 14, 1989
Suisman Titanium Corporation 500 Flatbush Avenue Hartford, Connecticut 06106	December 15, 1989
RMI Company Reactive Metals Incorporated 1000 Warren Avenue Niles, Ohio 44446	January 23 & 24, 1990
Titanium Metals Corporation of America Timet Division P.O. Box 309 Toronto, Ohio 43964	January 25, 1990
Titanium Metals Corporation of America Timet Division P.O. Box 2128 Henderson, Nevada 89015	February 5 & 6, 1990
Oremet Titanium Oregon Metallurgical Corporation 530 W. 34th Avenue Albany, Oregon 97321	February 7 & 8, 1990
Western Professional, Inc. (Westpro) 3480 Brady Court N.E. Salem Industrial Park Salem, Oregon 97303	February 8, 1990
General Electric Aircraft Engines 1 Neumann Way Cincinnati, Ohio 45215	February 27 & 28, and March 1, 1990

Materials Laboratory Air Force, Wright Research & Development Center Wright-Patterson AFB, Ohio 45433	March 2, 1990
Rolls-Royce plc P.O. Box 31 Derby DE2 8BJ England	March 12 & 13, 1990
Deeside Titanium Limited Deeside Industrial Park Deeside CLWYD CH5 2LL England	March 14, 1990
Smith-Clayton Forge P.O. Box 22, Tower Works Lincoln LN2 5DT England	March 15, 1990
IMI Titanium Limited P.O. Box 704 Witton Birmingham B6 7UR England	March 16, 1990
Cameron Forge Company P.O. Box 1212 Houston, Texas 77251	March 21, 1990
Garrett Engine Division Allied-Signal Aerospace Company P.O. Box 5217 111 South 34th Street Phoenix, Arizona 85010	March 27 & 28, 1990
General Inspection Labs 8427 Atlantic Avenue Cudahy, California	April 4, 1990 and subsequent dates
Textron Lycoming Stratford Division 550 Main Street Stratford, Connecticut 06497	April 5 & 6, 1990
Ladish Company, Inc. 5481 South Packard Avenue Cudahy, Wisconsin 53110	April 24, 1990

Allison Gas Turbine Division General Motors Corporation P.O. Box 420 Indianapolis, Indiana 46206	April 26 & 27, 1990
Dr. Alec Mitchell, Research Professor Department of Metallurgical Engineering University of British Columbia Vancouver, B.C., Canada V6T 1W5	May 10, 1990
Axel Johnson Metals, Inc. 215 Welsh Pool Road Lionville, Pennsylvania 19353	May 24, 1990
McWilliams Forge Co., Inc. Franklin Road Rockaway, New Jersey 07866	May 25, 1990

MEETING ATTENDEES

DECEMBER 11 & 12, 1989
and subsequent dates

PRATT & WHITNEY DIVISION. UTC

PAUL MEYER	CERTIFICATION & AIRWORTHINESS
GORDON SULLIVAN	NDT
JOHN J. KOPECKY	WASHINGTON, D.C.
BOB NORTH	PRODUCT INTEGRITY
DOUGLAS SCUSSELL	QUALITY
RICK SALKELD	ENGINEERING SOURCE APPROVAL
JON BERTUS	ENGINEERING SOURCE APPROVAL
HARRY LEMASTERS	DIRECTOR, COMMERCIAL ENGINE: CONTROLS, PERFORMANCE SYSTEMS, STRUCTURES, & PRODUCT INTEGRITY
ART LUCAS	MANAGER, SYSTEMS ENGINEERING AND TECHNOLOGY
BILL KNOWLES	MANAGER, ROTOR LIFE
JEFF HILL	RESEARCH ENGINEER

FEDERAL AVIATION ADMINISTRATION

JOSEPH COSTA	AEROSPACE ENGINEER, ENGINE CERTIFICATION
RAYMOND GONZALEZ	MANUFACTURING INSPECTION SPECIALIST
ROBERT GUYOTTE	MANAGER, ENGINE CERTIFICATION BRANCH
ROBERT KOENIG	AEROSPACE ENGINEER, TURBOFAN & TURBOJET ENGINE SPECIALIST
DANIEL SALVANO	ASST. MANAGER, AIRCRAFT ENGINEERING DIVISION
THOMAS SWIFT	NATIONAL RESOURCE SPECIALIST, FRACTURE MECHANICS

DECEMBER 13 & 14, 1989

WYMAN-GORDON CO.

ROGER BROADWELL	PLANT MANAGER
WAYNE EVERETT	QUALITY CONTROL MANAGER, EASTERN DIVISION
MARK ROUGHAN	SENIOR QUALITY ENGINEER
MICHAEL J. EDDY	SENIOR PRODUCT METALLURGIST
STUART J. CAMPBELL, JR.	QUALITY ASSURANCE MANAGER

FEDERAL AVIATION ADMINISTRATION

JOSEPH COSTA	AEROSPACE ENGINEER, ENGINE CERTIFICATION
RAYMOND GONZALEZ	MANUFACTURING INSPECTION SPECIALIST
ROBERT GUYOTTE	MANAGER, ENGINE CERTIFICATION BRANCH
ROBERT KOENIG	AEROSPACE ENGINEER, TURBOFAN & TURBOJET ENGINE SPECIALIST
DANIEL SALVANO	ASST. MANAGER, AIRCRAFT ENGINEERING DIVISION
THOMAS SWIFT	NATIONAL RESOURCE SPECIALIST, FRACTURE MECHANICS

MEETING ATTENDEES

DECEMBER 15, 1989

SUISMAN TITANIUM CORP.

JOHN LANE	DIRECTOR OF TECHNOLOGY
MICHAEL SUISMAN	CHAIRMAN & CEO
LEONARD WASSERMAN	PRESIDENT
MARK WINTER	VICE PRESIDENT

FEDERA N A INISTRATION

JOSEPH COSTA	AEROSPACE ENGINEER, ENGINE CERTIFICATION
RAYMOND GONZALEZ	MANUFACTURING INSPECTION SPECIALIST
ROBERT KOENIG	AEROSPACE ENGINEER, TURBOFAN & TURBOJET ENGINE SPECIALIST
DANIEL SALVANO	ASST. MANAGER, AIRCRAFT ENGINEERING DIVISION
THOMAS SWIFT	NATIONAL RESOURCE SPECIALIST, FRACTURE MECHANICS

MEETING ATTENDEES

JANUARY 23 & 24, 1990

RMI (REACTIVE METALS INC.)

ASHTABULA METALS PLANT

LARRY HANEK	MANAGER - QUALITY ASSURANCE AND PROCESS ENGINEERING
DICK HEISER	PLANT MANAGER
BRUCE NOLAND	MANAGER - PRODUCTION
JOE PETRARCA	SUPERVISOR - QUALITY CONTROL

NILES INGOT & BILLET PLANT

LOU BARTLO	GENERAL MANAGER, QUALITY ASSURANCE
JOHN KOSIN	MANAGER, CUSTOMER TECHNICAL SERVICE
JOHN MOYERS	NDT ENGINEER
BILL SCHOENFELD	VICE PRESIDENT, TECHNOLOGY & QUALITY ASSURANCE
DAVE SHELLITO	MANAGER, RAW MATERIALS & MELTING

FEDERAL AVIATION ADMINISTRATION

JOE COSTA	
RAY GONZALEZ	
DAN KERMAN	AEROSPACE ENGINEER, ENGINE CERTIFICATION, ANE-141
BOB KOENIG	
DAN SALVANO	

JANUARY 25, 1990

TIMET (Toronto, Ohio)

BRUCE BORIS	SUPERVISOR, INSPECTION AND NDT
FLOYD BROWN	SUPERVISOR, SPC
DON COOPER	VICE PRESIDENT, TECHNOLOGY & QUALITY ASSURANCE
BILL HEIL	CHIEF PRODUCT METALLURGIST
JIM MYERS	MANAGER, QUALITY CONTROL

FEDERAL AVIATION ADMINISTRATION

JOE COSTA

RAY CONZALEZ

DAN KERMAN

BOB KOENIG

DAN SALVANO

MEETING ATTENDEES

FEBRUARY 5 & 6, 1990

TIMET (Henderson, Nevada)

HOWARD PALMER	SUPERVISOR PROCESS CONTROL DEPARTMENT
J. A. TRINAYSTICH	SUPERVISOR PROCESS CONTROL DEPARTMENT
JAMES KING	QUALITY CONTROL ENGINEER
DONALD COOPER	VICE PRESIDENT, TECHNOLOGY AND QUALITY ASSURANCE
SCOTT McDANIEL	SENIOR PROCESS ENGINEER
WILLIAM YORK	SENIOR PROCESS ENGINEER

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

TOM SWIFT

MEETING ATTENDEES

FEBRUARY 7 & 8, 1990

OREMET

FRANK CAPUTO	PRESIDENT
JOHN P. LAUGHLIN	DIRECTOR OF METALLURGY AND QUALITY ASSURANCE

FEDERAL AVIATION ADMINISTRATION

JOE COSTA

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

TOM SWIFT

FEBRUARY 8, 1990

WESTERN PROFESSIONAL, INC. (WESTPRO) (NDI Lab) .

LAURENCE J. CHAMBERLAIN	PRESIDENT
RONALD SIEGRIST	LAB MANAGER

FEDERAL AVIATION ADMINISTRATION

JOE COSTA

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

TOM SWIFT

MEETING ATTENDEES

FEBRUARY 27 & 28, and MARCH 1, 1990

GENERAL ELECTRIC AIRCRAFT ENGINES

BRUCE VENABLE	MANAGER, AIRWORTHINESS & CERTIFICATION
FRED HERZNER	MANAGER, CF6 PRODUCTION OPS.
BILL BOGAN	PRINCIPAL ENGINEER, FA & AP
TERRY KESSLER	MANAGER, REPAIR PROCESS & NDE PROGRAMS
JOHN LANGFORD	MANAGER, CASTING, FORGING & MACHINED PARTS QUALITY
CHRIS McDANIEL	MATERIALS PROCESS ENGINEER TITANIUM
WALT VANDUYNE	SENIOR MANAGER, GROUP, FIELD
BOB RECCHIUTI	FLIGHT SAFETY INVESTIGATOR, FLIGHT SAFETY SECTION
AL KLASSEN	PRODUCTION SONIC INSPECTION
CLIFF SHAMBLEN	MATERIALS LAB

FEDERAL AVIATION ADMINISTRATION

BILL ALLEN	MANUFACTURING INSPECTION FIELD REPRESENTATIVE, NE-MIFR-OH
JOE COSTA	
RAY GONZALEZ	
BOB GUYOTTE	
BOB KOENIG	
DAN SALVANO	
TOM SWIFT	

MEETING ATTENDEES

MARCH 2, 1990

UNITED STATES AIR FORCE, WRIGHT RESEARCH & DEVELOPMENT CENTER

[illegible]	PROPULSION [ENSIP]
[illegible]	CHIEF MATERIALS INTEGRITY BRANCH
[illegible]	AERONAUTICAL SYSTEMS DIVISION
[illegible]	SENIOR NDE ENGINEER [MIL SPEC}
[illegible]	CHIEF, NDE BRANCH
[illegible]	TECHNICAL MANAGER, FAILURE ANALYSIS
[illegible] ARK	

FEDERAL AVIATION ADMINISTRATIO

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

MEETING ATTENDEES

MARCH 12 & 13, 1990

ROLLS ROYCE plc

JOHN MARPLES	ENGINEERING SPECIALIST - MECHANICAL TECHNOLOGY
RICHARD CORRAN	CORPORATE SPECIALIST - SOLID MECHANICS
GEOFF ASQUITH	CHIEF MECHANICAL TECHNOWGIST - MECHANICAL TECHNOLOGY
ADRIAN WALKER	ENGINEERING LABORATORY
CHRIS JONSON	HEAD OF MATERIALS - MECHANICAL TECHNOLOGY
TONY WASSELL	CHIEF AIRWORTHINESS ENGINEER
JOHN CASON	HEAD OF MANUFACTURING LABORATORIES
PAUL ALLEN	SUPPLY LABORATORIES TITANIUM METALLURGIST
RAY STOKES	MANAGER - EXTERNAL MANUFACTURING LABORATORY
HUGH K. CRAIG	MANAGER - NDT LABORATORY

CIVIL AVIATION AUTHORITY

REX RIDDINGTON	POWERPLANT SURVEYOR-IN-CHARGE, SAFETY REGULATION CROUP; BRISTOL
JEFF MABLESON	DEPUTY SURVEYOR-IN-CHARGE, SAFETY REGULATION GROUP; DERBY

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

MARCH 14, 1990

DEESIDE TITANIUM LIMITED

COLIN H. MORRISH	PRODUCT ASSURANCE MANAGER
NIGEL J. WINTERS	PRODUCTION MANAGER
GRAHAM MOORE	GENERAL MANAGER

IMI TITANIUM LTD.

TONY BARBER	TECHNICAL DIRECTOR
MALCOLM BRAWN	QUALITY MANAGER

CIVIL AVIATION AUTHORITY

REX RIDDINGTON	POWERPLANT SURVEYOR-IN-CHARGE, SAFETY REGULATION GROUP

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

MEETING ATTENDEES

MARCH 15, 1990

SMITH-CLAYTON FORGE

ALAN HOLEHOUSE	QUALITY MANAGER
JOHN E. LEE	CHIEF METALLURGIST
H. COOKSON	TECHNICAL DIRECTOR
DAVID J. JONES	MARKETING DIRECTOR

CIVIL AVIATION AUTHORITY

REX RIDDINGTON	POWERPLANT SURVEYOR-IN-CHARGE, SAFETY REGULATION GROUP

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

MEETING ATTENDEES

MARCH 16, 1990

JMI TITANIUM LTD.

J.' TAMBERLIN	. MANAGING DIRECTOR
TONY BARBER	TECHNICAL DIRECTOR
MALCOLM BRAWN	QUALITY/TECHNICAL MANAGER
A. WOOLCOCK	WITTON TECHNICAL MANAGER

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

MEETING ATTENDEES

March 21, 1990

CAMERON FORGE Y

COLIN STEAD	MANAGER, METALLURGY/QUALITY ASSURANCE
HAROLD TALBOTT	SENIOR QUALITY ENGINEER, METALLURGY/QUALITY ASSURANCE

FEDERAL AVIATION ADMINISTRATION

JOE COSTA

MEETING ATTENDEES

MARCH 27 & 28, 1990

GARRETT ENGINE DIVISION, A-SAC .

ALAIN DEVEAUX	AIRWORTHINESS
MICHAEL MORGAN	TURBOPROP PROJECT
ARLEN LARSON	TURBOFAN PROJECT
JAMES MARQUARDT	TURBOPROP FAA-DER
DUANE NAFF	PRODUCT INTEGRITY
DAVE SUNDBERG	MATERIALS ENGINEERING
GLENN PITTARD	MECHANICAL COMPONENTS DESIGN
FLETCHER H. BRAY	NON DESTRUCTIVE EVALUATION

FEDERAL AVIATION STRATI

JOE COSTA

BOB GUYOTTE

BOB KOENIG

TOM SWIFT

APRIL 4, 1990 and subsequent dates

GENERAL INSPECTION LABS

JOHN BARRIATUA	PRESIDENT
GARY SMALLEY	QUALITY CONTROL GENERAL MANAGER
BILL BULGER	SUPERVISOR, UT DEPT.

FEDERAL AVIATION ADMINISTRATION

JOE COSTA

MEETING ATTENDEES

APRIL 5 & 6, 1990

TEXTRON LYCOMING, STRATFORD DIV.

PAUL K. JODON	MANAGER, CERTIFICATION PROGRAMS
MICHAEL PISCATELLA	V.P. QUALITY ASSURANCE
LOU FIEDLER	MANAGER, MATERIALS/PROCESSES LAB.
WILLIAM CABRAL	DIRECTOR, PURCHASED MATERIAL QUALITY
DEAN WISLER	MANAGER, TURBOFAN CUSTOMER QUALITY
ROBERT HOGAN	QUALITY ENGINEERING/NDT
BRUCE DEBEER	MANAGER, ADVANCE STRUCTURE AND LIFE TECHNOLOGY
EDWARD BEARDSLEY	MANAGER, CERTIFICATION ADMINISTRATION
PETER CHANDLER	MANAGER, MATERIAL CONTROLS LABORATORY
WAYNE BURNETT	MANUFACTURING ENGINEERING
THOMAS LEONARD	MANAGER, QUALITY ENGINEERING
ARI TOMBOULIDES	MANAGER, VALUE ENGINEERING (PROCUREMENT)
SAJJAD AZIZ	PROGRAM MANAGER, ENGINE CERTIFICATION
STEVE LAMOND	MANAGER, QUALITY ENGINEERING SUPPORT
ALFRED A. BOUTIN	MANAGER, ALF502 ENGINEERING
LARRY PORTLOCK	MANAGER, ENGINEERING
MICHAEL GRIFFIN	MANAGER, CUSTOMER SUPPORT ENGINEERING
JERRY ROWLEY	MANAGER, MANUFACTURING INSPECTION

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

MEETING ATTENDEES

APRIL 23, 1990

LADISH COMPANY, INC.

GEORGE GROPPI	MANAGER, AEROSPACE METALLURGY
CARL JENSEN	LEVEL III MACRO ETCH
JIM KIRBY	MANAGER, METALLURGICAL OPERATIONS
PATT LEMSKY	ACCEPTANCE METALLURGIST
BOB MCATEER	MANAGER, PRODUCT ASSURANCE
BOB NOEL	MEETING CHAIRMAN; MANAGER, QUALITY & TECHNOLOGY
PAUL RIEPE	MANAGER, QUALITY STANDARDS
TOM SORCE	LEVEL III FLOURESCENT PENETRANT
HAROLD WALDAL	LEVEL III ULTRASONIC
BOB ZANONI	MANAGER, JET ENGINE METALLURGY

FEDERAL AVIATION ADMINISTRATION

DAN KERMAN

BOB KOENIG

APRIL 26 & 27, 1990

ALLISON GAS TURBINE DIVISION, GMC

NEVILLE EDENBOROUGH	PRODUCT ASSURANCE
LEWIS D. ESENWEIN	PRODUCT SAFETY: FAA DESIGNATED ENGINEERING REPRESENTATIVE
RAY FUNKHOUSER	DIRECTOR, PRODUCT DESIGN ASSURANCE
DON KLETNER	SUPPLIER QUALITY
BARRY ROHM	DIRECTOR, PRODUCT SAFETY: FAA DESIGNATED ENGINEERING REPRESENTATIVE
MALCOLM THOMAS	MATERIALS AND PROCESSES
DON VACCARI	STRESS ANALYSIS
DAVE WALKER	MANUFACTURING

FEDERAL AVIATION ADMINISTRATION

JOE COSTA	
DAN KERMAN	
BOB KOENIG	
TY KROLICKI	AEROSPACE ENGINEER, ENGINE CERTIFICATION, ACE-140C

MEETING ATTENDEES

MAY 10, 1990

DR. ALEC MITCHELL RESEARCH PROFESSOR, AND CONSULTANT, UNIVERSITY OF BRITISH COLUMBIA

FEDERAL AVIATION ADMINISTRATION

JOE COSTA LA

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

DAN SALVANO WASH DC

TOM SWIFT LA

9.B.22

MEETING ATTENDEES

M Y 24, 1990

AXEL JOHNSON METALS, INC.

WILLIAM ACTON	VICE PRESIDENT, SALES AND MARKETING
JANINE BOROFKA	CHIEF METALLURGIST
CHARLES ENTREKIN	VICE PRESIDENT, TECHNOLOGY
HOWARD HARKER	VICE PRESIDENT, MANUFACTURING & ENGINEERING

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

BOB GUYOTTE

BOB KOENIG

DAN SALVANO

MEETING ATTENDEES

MAY 25, 1990

McWILLIAMS FORGE CO., INC.

DONALD McWILLIAMS	PRESIDENT
GEORGE R. BITTNER	VP, ENGINEERING AND QA
ROBERT MANFREDONIA	METALLURGIST
WILLIAM ALLISTER	PROCESS ENGINEER
JOSEPH N. PASCOE	QUALITY CONTROL COORDINATOR

FEDERAL AVIATION ADMINISTRATION

RAY GONZALEZ

LAST PAGE

124 pages of text
26 Figures

150 total pages